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An Extinct Glacial Lake.

BY

HENRY BARNARD KÜMMEL, PH.D.

Presented as a Thesis for the Doctor's Degree,
The University of Chicago.
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INTRODUCTORY STATEMENT.

In the Annual Report of the State Geologist of New Jersey for 1880, Professor Cook made mention of a glacial lake which existed in the upper part of the Passaic drainage basin during the latter part of the Glacial epoch. The lake was stated to have covered the area of the Great swamp, the Black meadows, the Troy meadows, the Lee meadows, the Hatfield swamp, the Great Piece swamp and the contiguous low land. A number of localities, where evidence of the lake's existence were thought to occur, were cited. Because of its hydrographic position, the lake was called Passaic.* Although the boundaries of the lake were not traced out, its supposed level was determined at a few points. On the strength of these determinations, the area of the lake was represented on a map accompanying the report referred to. The average altitude of the border of the lake was stated to be 385 feet.

Later, Professor W. M. Davis visited the region, and observed what he interpreted as shore features at a number of points, but he never published his observations. In his further studies, he encountered what seemed to him grave difficulties in the way of the hypothesis which Professor Cook had put forth.

C. C. Vermeule,† in his description of the topography of New Jersey, made mention of a number of gravel terraces at elevations of about 400 feet, which showed that a lake existed in the basin between the Highlands and the Watchung mountains. He did not, however, discuss the data further than to call attention to the terraces.

During the field season of 1891, Professor Rollin D. Salisbury, in

*Annual Report of the State Geologist of New Jersey, 1880, pages 61–64.

†Geological Survey of New Jersey, Vol. I., Topography, pages 156–160.

connection with his detailed work in mapping the surface formations, brought to light many new facts, readily explicable upon the hypothesis of a glacial lake. These facts were presented and discussed by Professor Salisbury in the Annual Report of the State Geologist for 1892.* The data then at hand were sufficient to demonstrate, beyond reasonable doubt, the existence of Lake Passaic, but they were hardly sufficient to afford a clear insight into its history.

Further study of the lake was undertaken during 1893, more especially by the author of this paper for the purpose—1°, of gathering new data; 2°, of correlating more perfectly data already known; 3°, of explaining certain apparent contradictions and deficiencies; 4°, of working out the different stages in the lake's history, and 5°, of determining the possible changes, especially deformations, which the lake basin had undergone since the water disappeared from it. Two months of field work during the autumn of 1893 were given to this work. During a part of this time assistance was received from Mr. C. F. Sproul, an experienced surveyor and topographer, by whom were drawn the topographical sketches of shore features accompanying this paper, and with whose aid the heights of the various shore features were determined.

All the known facts concerning the lake have already been presented and discussed in a joint paper by Professor Salisbury and the author, published in the Annual Report of the State Geologist of New Jersey for 1893.† In that paper (page 225) Professor Salisbury has indicated the share which he and the writer had in the preparation of that report. The present paper gives in somewhat briefer form the facts concerning the lake and the conclusions derived from them, and is published with the permission of Professor Salisbury. For a more complete statement of all the details, the reader is referred to the joint paper mentioned above.

PRELIMINARY CONSIDERATIONS.

The trap ridges, known as the Watchung or Orange mountains, rise in long crescentic curves three and four hundred feet above the general level of the Triassic sandstone lowland on either side of them. The crescents are convex towards the southeast. The horns curve towards

* Pages 126-144.

† Pages 225-328.

the northwest and connect with the crystalline schist or gneiss highlands. The basin which is thus formed between the highlands on the northwest and the trap ridges on the south, southeast, east and northeast, is now drained in a very roundabout way by the Passaic river, which finally escapes across the trap ridges at Little Falls and Paterson. The height of the river where it crosses Second mountain at Little Falls is 158 feet.

Leaving out of account the low line of drainage along the Pompton river at the north, which, when the lake existed, was closed by the ice sheet, there is no other break in the rim of the basin lower than 331 feet. At this height there is an outlet across the trap mountains at Moggy Hollow, about two miles west of Liberty Corner, in the southwestern part of the basin. The altitude of the Great swamp is about 230 feet, and therefore about 100 feet below the Moggy Hollow outlet. Within the basin thus inclosed, rise several smaller trap ridges, of which Long Hill, extending from Chatham to Basking Ridge, is the most important. The trap hills near New Vernon (south of Morristown), Livingston, and Whitehall and one or two hills of Triassic conglomerate or hard shale near New Vernon rise about two hundred feet above the surrounding lowlands. Between Chatham and Morristown the terminal moraine forms a ridge 100 to 250 feet above its surroundings. This ridge divides the topographic basin into two parts.

Such being the drainage and topography of this region, there is *a priori* reason for believing that when the ice sheet blocked the outlet of the Passaic at Little Falls or Paterson and filled the Pompton valley to the north, a lake was formed in front of the ice, in the basin between the gneiss highlands on the northwest and the crescentic trap ridges on the southeast, unless at that time there was a gap across the trap ridges south of Little Falls. As will be shown later, well borings prove that there is a deep drift-filled gap across the trap ridges near Short Hills and Millburn. The depth of the rock bottom of this gap renders it certain that a large part of the pre-glacial drainage of the present Passaic basin was across the trap ridges at this point. The pre-glacial drainage of the northern part of this basin probably escaped by the gaps at Little Falls and Paterson. The two drainage systems could have been separated by no more than a low divide.

A part of the drift in the Short Hills-Millburn gap may be first glacial. If any considerable proportion of it is of this age, all the

inter-glacial drainage may have escaped via Little Falls and Paterson. If this was the case, it is possible that the drainage held its course beneath the ice for a shorter or longer time after the edge of the same had reached the Little Falls outlet across the trap ridge; but it is difficult to believe that such could have been the case, after the ice had advanced any considerable distance beyond Little Falls. It is well-nigh incredible that such a sub-glacial drainage outlet could have persisted until the ice occupied the position marked by the terminal moraine at Morristown and Madison. If the sub-glacial outlet did not persist, and if the drift in the Short Hills gap is largely early glacial, Lake Passaic must have existed long before the ice reached the line of the moraine.

If, on the other hand, all or by far the greater part of the drift in the Short Hills gap is last glacial, as is quite probable, the lake would not have been formed until the ice had closed this outlet. A small lake, however, might have existed in the basin of such stream as flowed through the Little Falls gap, after the ice had closed that outlet. Such a lake, if it existed, must have been shallow, as it would have overflowed the low divide into the basin of the river, which flowed through the Short Hills-Millburn gap. When the ice had advanced to the line of the terminal moraine it must have filled the Short Hills gap. It would seem, therefore, that Lake Passaic must have existed during and after the time when the ice held this position.

Barring the outlets at Little Falls and Paterson, the lowest point on the rim of the basin which enclosed the lake is the notch near Liberty Corner, at an elevation of 331 feet. Through this notch the lake, if it existed, must have drained.

As the glacier retreated from the position of the terminal moraine the lake must have increased its area by occupying those parts of the basin from which the ice successively withdrew, until at length its waters were able to escape either under the ice or through the gap at Little Falls. When the recession of the ice opened the Little Falls outlet again, the water of the lake must have fallen promptly to the level of the outlet. If this outlet was much higher than now, the lake must have continued a diminished existence until the outlet had been cut down nearly to its present level.

If the lake existed, as above outlined, it was naturally divisible into two parts—the extra-morainic and the intra-morainic. The former occupied that part of the basin lying southwest of Morris-

town, Madison and Chatham, extending to Basking Ridge and Union Village. It included the Great swamp and the surrounding areas below the level of the outlet at Moggy Hollow. This part of the lake had a longer, or at any rate, a more interrupted history than the other, and so far forth the record of its existence should be more distinct. The intra-morainic portion of the lake extended from the moraine on the southwest to Boonton, Montville and Pompton Plains on the north, to Caldwell on the east, and to Summit on the south, including Black meadows, Troy meadows, Great Piece meadows and Hatfield swamp, besides considerable areas of higher ground.

If Lake Passaic existed, that fact ought to be capable of more or less complete proof. Even if its life were short, the lake must have left sufficient record of itself to place the fact of its existence beyond question.

This record would be expected to consist of (*a*) shore features, (*b*) berg deposits, (*c*) lacustrine deposits, (*d*) something of a difference between the pre-lacustrine surface formations within and without the lake area, and (*e*) a difference in the nature of the till within the lake basin and that without. These differences last mentioned may be very slight; they may not be recognizable at all points, and may be difficult of detection at most; yet they might reasonably be expected to exist. The presence of unmistakable shore features, even in the absence of the other lines of evidence, would prove the existence of the lake. If shore features were altogether absent, all the other lines of evidence might be inconclusive, since berg deposits, lacustrine deposits, lacustrine-like modifications of till and of other surface formations may be simulated more or less closely by other agencies. While no one of these other lines of evidence might be conclusive, their combined testimony might have great weight. Yet if the lake had so protracted an existence as to develop these various phenomena in such strength as to make them available in evidence, it could hardly have failed to develop recognizable shore features. The chief reliance must be placed on shore features. The other lines of evidence may have much corroborative interest and weight.

One of the principal conditions which control the development of shore features and lacustrine deposits is the time element. Other things being equal, a lake with a long life would bring about a better development of shore features and lacrustrine deposits than one of briefer history. Relying on this principle, it is possible to make

some inference concerning the length of life of an extinct lake from the degree of development of its shore features.

Another factor determining the distinctness of the shore features of lakes is their size. The larger the lake, the greater the sweep of its waves, and, other things being equal, the better the development of its shore features.

After a lake is drained and its shore features are exposed to the ordinary agents of sub-aërial erosion, they may soon lose their distinctness. If, therefore, we find wave-cut cliffs and terraces sharp and distinct; spits, bars, beaches, and deltas with normal profiles, and but slightly gullied by post-lacustrine erosion, we may safely infer that post-lacustrine time has been short and that the lake was drained but recently. If, on the contrary, the shore features are indistinct, and if this indistinctness can be shown to be due not to lack of original development but to subsequent destruction, we must conclude that post-lacustrine time has been long.

If the history of an extinct lake was a complicated one, involving various stages during which the water stood at different levels, shore features may be preserved at various altitudes. From the nature and relations of these various sets of shore features, something of the history of the lake may be read. Under favorable conditions, the record of the events of a lake's life may be very complete. If shore features were distinctly developed at the successive levels of a lake, if they are well preserved, and if their relationship to each other is clearly and unequivocally shown, the history of the lake may be made out with great clearness and detail. In so far as the record is fragmentary, or in so far as these conditions are not all fulfilled, the history of the lake remains obscure in some or all its parts. It may be here added, in anticipation of that which is to follow, that the shore features of Lake Passaic are not, at most points, conspicuously developed, and that their obscurity is plainly not the result of subsequent erosion. It must be inferred that they were never well developed. Since the size of the lake was sufficient to have allowed of waves of several miles fetch, the meager development cannot be ascribed to the smallness of the lake. It is, therefore, concluded that the life of the lake was short. The evidence is sufficient to show that the history of Lake Passaic was not a simple one, but the record is not sufficiently complete or definite to make it possible to decipher with certainty all its stages.

THE SHORE FEATURES OF LAKE PASSAIC.

When search is made for shore features about the borders of the supposed Lake Passaic they are found to exist, but not in so many localities nor in such strength of development as might have been anticipated. They are absent from some localities where their presence might have been expected, and they are sometimes well developed where there seems to be no good reason for their distinctness. Careful study has demonstrated that their absence at certain points and their indistinctness at others is due primarily to failure of original development, not to subsequent destruction. Nevertheless, indubitable shore features are found at so many places as to prove the existence of the lake. In many instances the features found are not so distinct as to be indubitable. But here, as in the study of very many geological questions, the effect of the evidence is cumulative. As each new fact or series of facts touching the existence of the lake was found, it was seen, not only to accord with the hypothesis of the lake, but to be demanded by it. Two concordant and corroborative facts, or series of facts, have a value much more than twice as great as that of one, so far as their bearing on any particular hypothesis is concerned. On the same principle, four corroborative facts, or series of facts, are worth much more than twice as much as two. As corroborative facts concerning Lake Passaic were gathered, though some of them were not in themselves indubitable, their cumulative force became such as to compel belief in the existence of the lake.

In describing the various shore features of Lake Passaic, the extramorainic portion will first be considered. The various classes of shore features will be taken up in succession, and their nature and geographic distribution noted. This can best be done by beginning with that part of the basin near Summit, and passing around the lake to the southwest.

The elevations which are given in the following pages were in most cases determinded by two men working with a surveyor's level and rod. From the original sheets of the topographical atlas of the State, the heights of the centers of road intersections, of road summits, of brook crossings and of cols were obtained. As taken from the map, these are supposed to be correct to within fractions of a foot. From these bench-marks, which were usually at intervals of not more than

half a mile, lines of levels were run to the desired points. Wherever it seemed possible that an error might creep in through inaccuracy in locating the bench-marks, the levels were continued to the next bench-mark, or sometimes to several bench-marks. In this way possible errors in the heights of the bench-marks because of grading or filling of the roads since the topographical survey was made, were guarded against. The elevations thus determined are believed to be correct to within one foot. In a few cases the heights were determined from a bench-mark close at hand, by a hand-level, and here the possible error may be as much as three or four feet. Unless otherwise stated, the heights given are those determined by the more accurate method.

A. THE EXTRA-MORAINIC PORTION OF THE LAKE.

I. Possible Wave-cut Terraces and Cliffs.

At numerous points along the shore of the extra-morainic basin, cliffs and terraces were found at elevations which correspond more or less closely with the height possessed by the waters of the lake. In the majority of cases these cliffs and terraces are so poorly developed that it is impossible to assert positively that they were formed by the waves of the lake. In themselves they cannot be regarded as demonstrative proof of the existence of the lake. Especially is this true since lake terraces are closely simulated by terraces formed in other ways. But since, by other lines of evidence, the lake is known to have existed the presence of the best marked of these cliffs and terraces becomes important corroborative evidence.

The exact location of these cliffs and terraces is shown upon the accompanying map. Terraces designated by A 1,* A 2, A 3, A 5, A 6, C 6, C 11, D 1 and D 3 are referred to the waves of the lake with more or less doubt, since the evidence of such origin is not conclusive. Terraces C 3, C 4, C 5, C 7, C 8 and D 2 are probably due to other causes. In the case of terraces A 4, B 1, B 2, C 1, C 2, C 9 and C 10 the evidence in favor of a lacustrine origin is stronger, and they were probably formed in this way. The data concerning them are as follows:

A 4. *Liberty Corner outlet.*—A mile and a half west by north of Liberty Corner, at Moggy Hollow, is the notch in the trap ridge, at

*For a detailed statement concerning each of these terraces, the reader is referred to the joint paper by R. D. Salisbury and H. B. Kümmel, loc. cit.

an elevation of 331 feet, by which the waters of the lake drained into the valley of the North Branch of the Raritan. A full discussion of the outlet will be made the subject of a later section, but here attention ts directed to the probable wave-cut terraces in this vicinity. In the peach orchard of Mr. Henry Apgar are numerous small outcrops of trap, around which it is evident the waves of the lake beat. The trap rock is covered by only a thin layer of soil, and around the knolls of rock slightly but certainly water-worn trap pebbles are found. To the observer whose eye is focused to catch the slightest trace of horizontal cutting by the waves, the terrace is distinctly visible. By another it may be readily overlooked, since it is not accompanied by a distinct cliff. The phenomena are such as would be produced on a gently-sloping, rocky shore against which the waves had beaten but a short time, and where the finest material had been carried off, leaving the ill-rounded pebbles just where they originated. They are not the phenomena of a shore where any marked terrace and cliff had been cut. Both above and below the zone thus affected the rock is covered by a much deeper layer of residuary soil. No well-marked beds of wave-worn gravel could be found in the immediate vicinity. The height of the mean lake level at this point was between 351 and 356 feet.

B 1. A little more than a mile northeast of Bernardsville, on the gneiss highlands, there is a narrow bench which can be referred with some certainty to wave action. It is distinctly marked, and passes southward into a wave-built, terrace-like spit of sand and gravel, evidently products of wave erosion. This sand and gravel will be described later. The terrace can be traced northward for three or four hundred yards. Its height averages 370 feet.

B 2. *Near Morristown.*—For a mile and a half southwest of Morristown, along Mount Kemble avenue or the Mountain road, there is a narrow terrace which in places is fairly distinct. The road is located upon it for some distance. This terrace forms a bench in the steep slope of the hillside. The slope rises rather abruptly above its upper edge, and falls off with almost equal abruptness at its outer edge. In places, the distinctness of the terrace has been increased by grading and filling, and in other localities, as shown by cuts, it has been obscured by post-lacustrine wash. It is partly wave-cut, and partly wave-built. In a number of places a thin layer of sand and

water-worn gravel was noted, and at one cut the following section was seen, commencing with the surface:

3. Clay, containing some grit and sand, with a few gneiss fragments, very compact, glazing slightly when cut, and cracking on the dry face; thickness, three to four feet.

2. Rounded gravel, mostly gneiss, but with a few foreign pebbles; pebbles generally small and more or less imbedded in a clayey matrix, but sometimes very loose; thickness, six inches.

1. Gneiss residuary, containing angular, unworn fragments.

The upper member of the section was such as might well be derived from the finer clayey part of the gneiss residuary of the higher slopes by post-lacustrine wash. The thin gravel layer between this and the unmodified gneiss residuary is believed to be due to wave action. The few small foreign pebbles could readily have been derived from the overwash plain and carried along the beach by littoral currents and waves.

The height of this terrace is about 365 feet, but, as will be seen later from other evidence, it does not mark the maximum level of water at this locality.

C 1. On the north end of Long Hill, half a mile south by west of Chatham depot, is a strongly-marked wave-cut cliff and terrace. This part of the hill is covered with till, and, as it was exposed to a long sweep of the waves from the north and northwest, the terrace and cliff are well developed. The cliff rises by a steep slope from the terrace, on which are strewn a number of large trap, gneiss and quartzite bowlders, evidently washed out of the till. Some of these are four or five feet in diameter, but the average size is two to three feet. At several points on the terrace the bare trap is exposed, indicating that the terrace was a place of erosion rather than of deposition. The upper edge of the terrace has an altitude of 369 feet, and is sharply defined; the lakeward margin passes gradually into the general slope of the hill below and cannot be definitely located.

This wave-cut terrace can be traced southward along the eastern side of Long Hill. Its surface there becomes sandy, and it soon passes into the prominent wave-built terrace seen in the lower part of Chatham cemetery. The clearly-defined cliff, the bowlder-strewn terrace, its association with and transition into the prominent wave-built terrace, make this one of the best-marked shore features of the extra-morainic basin.

Along the southeastern or front face of Long Hill, terraces and cliffs may be observed in several places, but probably not all of them, and perhaps none of them, are to be connected with the lake. The upper part of the hill is composed of trap which is underlain by the Triassic red sandstone and shale. The face of the trap is generally marked by a steep slope which changes abruptly to a more gentle one a little below the contact with the softer red shale. The junction of the shale and trap is frequently near the level at which the waters of Lake Passaic stood. The benches and cliffs on the south face of Long Hill may therefore be benches and cliffs of differential degradation. Such topographic features may simulate very closely ill-defined wave-cut cliffs and terraces, and it may not always be possible to distinguish between them. In studying the possible wave-cut terraces of Lake Passaic, those terraces which were not directly traceable into wave-built terraces, spits or beaches, were regarded as probably wave-cut when they corresponded in elevation with neighboring shore features about which there was no doubt. Even this accordance cannot be said to prove their lacustrine origin, but only to render it probable. It is possible that a cliff and terrace due to differential degradation in pre-lacustrine times should occur at the lake-level, but in this case we should expect it to have been more or less re-shaped and intensified by the action of the waves. This would also be the case with all differential degradation benches which occur at any level at which the lake stood for any considerable period. It may be, therefore, that some cliffs and terraces at the maximum shore-line, as well as at lower levels, owe their location primarily to other than lacustrine factors, but they may have been more or less altered by the waves. This may be the reason why in some localities cliffs and terraces are so prominent, while in other places, apparently equally favored, they are obscure or altogether wanting.

C 2. *New Providence.*—Along the face of Long Hill, northwest of New Providence, there is a narrow but well-marked bench at the upper edge of which is an abrupt change to a steeper slope. The bench has been cut in the red shale, the contact of the trap and shale being at least thirty feet above the bench. It does not seem, therefore, that the bench is due to contrasts in hardness between the shale and trap. Since its elevation is 367 to 369 feet, and it can be traced almost continuously into a well-marked spit a mile west of New Providence, it can, it is believed, be safely referred to the lake,

although no deposits of wave-worn pebbles or sand could be found along its outer margin. At the lakeward edge of the bench foreign pebbles and cobbles occur, but since there is good evidence that a tongue of the glacier stretched down this valley a few miles beyond the moraine, these erratics and accompanying sand are probably due to the ice rather than to the lake. This bench can be well seen from Murray Hill station, its upper edge in general corresponding with the lower edge of the woods.

C 9. *Liberty Corner.*—A mile and a half northeast of Liberty Corner are two trap hills which were islands in the lake. On the south side of each of them there is a terrace and cliff, a distant view of which can be had from the Liberty Corner-Millington road. The eastern one is at an elevation of 350 feet, and is developed in the shale. Forty or fifty feet above it is another bench, along the contact of the shale and trap, which is clearly due to differential degradation. On the surface of the lower terrace traces of water-worn shale and trap gravel were observed, generally more or less buried by a red clay, which may be, in part at least, post-lacustrine wash. Although the upper edge of this terrace is six or eight feet below the level of well-marked water-worn trap gravel found in the immediate vicinity, it still seems referable to the action of the waves. The cliff rises about twenty feet above the terrace and is marked by a number of shale outcrops.

C 10. The other cliff and terrace is half a mile west of the one just described. Its height is 349 feet, and, as in the other case, traces of water-worn shale and trap pebbles were found upon it, beneath a thin layer of clayey material. Since this terrace is located near the line of contact between trap and shale, the terrace may be due in part at least, to differential degradation and have been only emphasized by the waves.

II. Wave-built Shore Features.

The wave-built shore features in the extra-morainic basin of Lake Passaic are more readily and more certainly recognized than the wave-cut features. They consist of spits, terraces, certain beds of water-worn gravel which do not possess marked topographic form, and scattered water-worn pebbles. The location of all of these deposits is shown upon the accompanying map; the more important of them are here described.

a 12. In the vicinity of the corner, a half mile east of Bernardsville, and one mile north of Basking Ridge, is an extensive (for Lake Passaic) wave-built terrace of gravel. Its greatest length, 2,400± feet, is along the road to Basking Ridge, and its greatest width is 1,500± feet. The gravel reaches a maximum elevation of 367–9 feet. Along the roads north, east and south of the corner there are exposures which show considerable variation in the constitution of the gravel. In the cuts north and south of the corner the gravel is made up largely of flat, disk-like pebbles of red shale, the once-angular corners entirely rounded. A few pebbles of trap, gneiss, slate and quartzite are also found. In the cut along the road toward Madisonville the gravel contains much less red shale and a much larger percentage of trap pebbles. The gneiss, slate and quartzite pebbles are also found.

This terrace is built at the head of what was a small bay, the headlands of which were, on the northeast, trap, and on the south, a surface covered by earlier glacial drift and red shale. Materials from each of these sources therefore occur in the terrace. The great development of this deposit, compared to most of those found about the borders of the lake, is due (1) to its favorable situation for accumulation—the head of a bay—(2) to the prominence of the headland of trap, (3) to the erodable character of the drift and red shale, (4) to the wide sweep of the waves from the east. A well near the corner penetrated fifteen feet of more or less compact gravel and then struck "red clay," which may have been nothing more than clayey shale. A depth of thirty feet of gravel has been reported.* This gravel lies mostly on the properties of James V. Blazer and Calvin D. Smith.

a 13. Half a mile north of the above corner, in a shallow bay north of the trap headland, is a small deposit of water-worn gravel, mostly trap, but with some shale and gneiss. It is exposed to a depth of six feet along the road, and, in the amount of rounding and wear which its constituent pebbles have suffered, it is in marked contrast to the angular trap fragments above the lake-level. The gravel does not appear at the surface above 360 feet, but its upper limit is obscured by post-lacustrine wash. It is on the property of Mr. Childs.

b 1. A little northwest of the above deposit, near the head of a small bay between the gneiss and trap, is a small but distinct

*Annual Report of the State Geologist of New Jersey, 1892, page 133.

spit, whose shoreward margin has an altitude of 371 feet, and whose distal end is 365 feet A. T. The gravel is composed almost entirely of gneiss, with occasional pebbles of Triassic red shale, Hudson river shale and quartzite, but it contains practically no trap. Since the trap hill is but a few rods away, the absence of trap is significant of the direction of the waves, which must have been from the northeast along the gneiss highland. The littoral current set along this side of the bay, and, dropping its load nearly at the head of the inlet, built this spit, which reaches almost to the trap hill on the other side. Traced shoreward the spit is continuous with a wave-cut terrace (B 1) thirty yards wide, the outer edge of which is marked by a few gneiss bowlders, but upon which no trace of gravel could be found. A pit has been opened in the end of the spit, which is on the property of Mr. Childs.

If water should rise to a height of 360 ± feet about Long Hill, there would be formed a series of nine long, narrow islands, rising to heights not exceeding 125 feet, and in general separated from each other by narrow, shallow straits. Debris carried by the waves and currents along the shores of these islands would accumulate at their ends as spits, bars, or beds of gravel and sand without definite topographic form. By these deposits the islands would in time become connected, or at least the channels between them would be diminished both in depth and breadth. When the cols of Long Hill are examined, either beds of trap gravel, or water-worn trap pebbles, are found at accordant heights between each pair of the former islands. The presence of these water-worn beds of locally-derived gravel in just the positions where they might be expected to accumulate as the result of wave action if the lake existed, at the proper height, and where their origin by any other means seems impossible, is in itself a strong proof of the existence of Lake Passaic. The following are the more important of these beds.

c 1. In the lower part of the cemetery of Chatham, and just north of the paper mills on the Passaic river, is a high, well-marked wave-built terrace of sand and gravel. At its northern end it is continuous with the wave-cut terrace at the north end of Long Hill. (C 1.) Towards the south it terminates in a short, spit-like projection. It is composed of glacial gravel, derived from the till which covers this end of Long Hill. At its upper edge it is 369 feet A. T. From this point there is a gradual slope to 351 feet, where it falls off more

steeply. This terrace can be traced for more than a third of a mile along the side hill; it varies in width, being widest opposite the cemetery (440± feet), and narrowing northward. A good view of this terrace can be had from the southeast, across the river.

c 3. A mile and a quarter west of New Providence is the sag which separated the first island of Long Hill from the second, counting from the northeast. At the southwest end of the first island is a short but pronounced spit. Northeastward it is continuous with the wave-cut terrace (C 2); southwestward, the free end terminates just back of Mr. Samuel Durie's house. From its upper edge, about 350 feet, it slopes gradually to 335, and then plunges off steeply for seventy or

Fig. 1.

Durie spit and surroundings represented by contour lines. The spit is near the center of the map, extending just south of west from the 360 line. Scale, three inches to the mile.

eighty feet. From the low hill, half a mile to the southeast, a good profile view can be obtained. In the pit which has been opened near Mr. Durie's house, the material is seen to range from fine sand to pebbles six inches in diameter, with rarely a small bowlder a foot to a foot and a half in diameter. The finer constituents are very largely of red shale, which also comprises much more than one-half the larger pebbles, although fresh gneiss, red sandstone (unidentified), quartzite, trap, greywacke and slate pebbles are more or less common. The shale pebbles are disk-like in shape, and, owing to their abundance, the gravel as a whole has this characteristic form. Since the pit is in the end of the spit, the structure is well shown. Along the axis of the spit the beds are seen to dip in the direction of the free end, whereas on the sides they dip outward, forming what may be called anticlinal stratification.

Some of the layers are of fine, clean sand; others are of loose gravel, the interstices between the pebbles not being filled; others are

of pebbles which are coated with a film of clay, and by this means loosely cemented together. The clayey layers are in the upper half of the gravel.

c 5. Rounded trap pebbles can be found more or less continuously along the inner (northern) slope of Long Hill for nearly a mile southwest of the above locality. Within this distance a ditch was found, which had been dug for several hundred feet directly across the old shore line. This exposure was the more valuable in that the surface did not show any topographical evidence of wave action, nor were wave-worn pebbles abundant on the surface. Above an elevation of 361 feet the material exposed in the trench was trap residuary,

Fig. 2.

Cross-section of the Durie spit, showing the general tendency to anticlinal structure. (Drawn from a photograph.)

the rock fragments being deeply decayed, angular, or but slightly rounded by exfoliation. At 361 feet there was a change. The trap residuary was succeeded laterally (lakeward) by coarse, water-worn, rounded, more or less fresh-looking trap pebbles, the whole somewhat stratified and containing occasional foreign pebbles. Farther out, the gravel passed beneath fine sand, which was succeeded by gravel, and that again by sand. A thin layer of clayey loam covered the whole, effectually concealing the gravel, except where exposed in the trench.

This exposure was valuable for several reasons. (1) It proved conclusively that some agent had been at work upon the lower part

of the slope, re-working and re-arranging the trap residuary up to a certain definite point, above which it did not reach. The element of height was the only controlling factor. Waves working at this height could produce the observed phenomena; running water, either as streams, causing surface wash, or percolating water, causing creep, could not. (2) This exposure was valuable in that it furnished a definite point by which to fix the lake-level (361 feet). (3) It showed conclusively the fact that the absence in some localities of topographic shore features, and of rounded gravel on the surface, does not militate against the lake hypothesis; and (4) it furnished a strong presumption that shore gravel has a much wider distribution than at first appears, and that it has been buried in post-lacustrine time beneath a thin layer of surface wash, sod and vegetable mould.

c 7. Half a mile south by west of the gap, a mile northwest of Berkeley Heights station, there is a terrace at 311 feet, at the western end of which is a short but sharply-marked spit, whose upper edge coincides with the terrace, and whose distal end declines to 270 feet, where it terminates in a steep slope. The gravel is largely of red shale, but trap gneiss, slate, greywacke and quartzites are by no means rare. As this spit and terrace are forty-five to fifty feet below the maximum lake-level of this vicinity, they must be referred to a stage in the lake's history when the water was below its maximum level.

c 8. On the road leading over the mountain eastward from Long Hill village, and a third of a mile from the same, is a small but typical exposure. By the roadside, at an elevation of 360 to 362 feet, are a number of large, rounded water-worn trap bowlders, in the crevices between which are sand and fine gravel—exactly what would occur where waves beat upon a rocky shore. Near here are also several outcrops of trap, the thin soil covering of which was probably removed by the waves. In the fields for some distance on either side of the road, scattered rounded pebbles were noted. The shore line here is not marked by any considerable accumulation of gravel.

c 11. Trap gravel can be traced along the north and west sides of the hill lying just north of Millington station. The gravel reaches a height of 361 feet, and in places forms an indistinct terrace. In the railroad cut on the west side of this former island, the gravel is seen to be distinctly stratified, to be about twenty-five feet thick, and to

range from coarse sand to ill-rounded cobbles five or six inches in diameter. Nearer Millington station is an exposure of red shale. On the part nearest the trap, the shale is covered by one to three feet of trap gravel, which gradually changes to shale gravel as it gets farther from the trap.

On the hill to the west, across the gorge, rounded pebbles of trap were noted, together with a few of gneiss, as high as 355 feet, but there are no considerable beds of gravel.

c 12. Half a mile south of Lyons station, along the road which passes between two trap hills, is another pit in a bed of trap gravel which accumulated in the shallow water between the two islands. The deposit is not extensive, though its limits cannot be well made out for lack of exposures. In the pit, the gravel is seen to vary in thickness from three feet to more than eight feet. The pebbles under one inch in diameter are well rounded, but the angularity increases with the size. Where exposed, the gravel is obliquely stratified, though the stratification is not especially distinct and contains no layers of sand. Its upper limit, which marks very closely the actual water-level, is 361 feet A. T. The deposit is on the property of Benjamin Runyon.

c 13. A mile southwest of the last, on the parallel road, is another bed of trap gravel, likewise in the narrow channel between two islands. Its greatest length is in the neighborhood of 1,200 feet, and its width about three-fourths as much. In a pit toward the northern end the gravel attains a thickness of over eighteen feet. Here it is almost entirely of trap, the pebbles ranging upward to six or seven inches in diameter, but averaging less than two inches. Towards its southern limits the gravel contains a noticeable element of red shale, which was derived from the wave-cut terrace in the red shale a short distance to the east. (C 9.) This gravel reaches up to a height of 356 feet. It occurs on the property of Lawyer Zieglow and of Dominie Bowers.

c 14. Half a mile north of Liberty Corner are two small hills of trap, whose crests rose just above the surface of the lake. At the southern end of the northern one is a broad, flat-topped spit, about 300 yards long and 200 yards wide. In a pit near the road there is exposed twelve feet of coarse (constituents ranging up to one foot in diameter), poorly-rounded, obliquely-stratified trap gravel, the beds

of which dip outward towards the periphery of the spit. This gravel pit is owned by Bernards township, and the material is used on the roads. This spit is 348 feet A. T. at its highest point. A few rods to the southeast is the other trap knoll, at the northern end of which is another spit, which, at its end, coalesces with the one already described. This spit is owned by Charles Greulock. Its greatest height is 342 feet A. T. Judging by the heights of the gravel beds to the east, mentioned above, and by the phenomena at the outlet, these beds are eight to fifteen feet below the maximum lake level in this region.

c 15. A little north of Lyons station, south of the fork of the roads, is an extensive deposit of trap gravel, forming a wave-built terrace, 100 to 150 yards wide. This is at the southern end of what was a peninsula, and is a favorable point for the accumulation of debris transported along its eastern and southeastern sides. The deposit is best shown in the pit at the crossing of the Basking Ridge-Liberty Corner road and the railroad. Here coarse trap gravel is seen overlying and horizontally inter-stratified with coarse sand. The pebbles average two to three inches in diameter, but range upward to ten inches. Ninety-nine per cent. of the material is trap, the foreigners being gneiss, slate and quartzite. Five per cent. of the larger and probably thirty per cent. of the smallest material might be called well rounded. Most of the pebbles not included in this class show signs of wear. Those showing no signs of rounding vary from fifty per cent. of the largest pebbles to only five or ten per cent. of the smallest. The gravel here reaches a height of 364 feet.

Northward from this terrace, through the timber and in the cultivated land along the foot of the trap escarpment, rounded pebbles of local origin were observed in considerable numbers. As the red shale at Basking Ridge is approached, the shale pebbles become more numerous, and the trap pebbles become proportionally less abundant. Water-worn shale pebbles were noted around newly-set fence posts, just back of Moore's hotel, although on the surface no signs of gravel were to be seen.

c 16. Southwest of Moore's hotel, Basking Ridge, is a broad wave-built terrace at the head of a small bay. From this point the terrace can be traced for half a mile northward on both sides of the railroad track. The gravel was derived largely from the local shale, the peb-

bles being flat, disk-shaped and covered with a thin film of fine clay. Nothing is known as to its depth save that it exceeds six feet. Northward from this terrace rounded pebbles were noted at heights varying from 360 to 365 feet, and in a ditch near the railroad station the reworked upper part of a bed of till belonging to an earlier ice invasion was seen. The lake level in the vicinity of Basking Ridge was very nearly 367 feet A. T.

d 1. A quarter of a mile west of New Vernon is a wave-built terrace ending in a small spit extending southward nearly across what was, in the days of Lake Passaic, a small bay. The material is largely red shale gravel with some pebbles, which may be from the drift or from the Triassic conglomerate of the vicinity. The top of the spit has an elevation of 372 feet, and at its end it falls off abruptly twenty feet. The terrace extends northward to the road, where it is interrupted by a deep gully, beyond which it can be traced more or less clearly for half a mile in a slightly-sinuous course to the northeast. In this direction it departs slightly from the shore, and assumes something of a spit-like appearance, at the same time declining a few feet in height. Much of the material is quartzite from the Trias conglomerate.

d 3. A mile east of New Vernon are five more or less topographically-distinct constructional terraces, which are clustered about a small hill of red shale rising ten feet above the lake-level. They are within an area less than a quarter of a mile square, but nevertheless show slight variation in altitude, their heights being 370, 371, 373, 376 and 376 feet, respectively. This gives an average height of 373 feet. There are no exposures, but from surface indications the material seems to be well rounded. It is composed of disk-shaped red shale pebbles and sand.

d 5. A mile and three-quarters due south of the Morristown depot is a spit-like deposit of trap gravel, at the northern end of the trap ridge which extends northward from Green Village. Occasional fresh gneiss and quartzite pebbles, derived either from the drift close at hand, or borne in by floating ice, are found in the gravel, which otherwise is composed entirely of poorly-rounded trap pebbles. The gravel was noted on the surface up to a height of 381 feet, but the indications from the topography are that the lake-level was about 376 feet. If this was the case, the height of the lake at this locality is

brought into accord with the heights of the nearest shore features to the west. The longitudinal profile of this deposit is interesting. From the highest point (381 feet) at which gravel was noted, the surface declines thirteen feet in the first seventy-five yards (1 in 17), fifteen feet in the next twenty-five yards (1 in 5), eighteen feet in the next 125 yards (1 in 21), and then thirty-five feet in the last seventy-five yards (1 in 6), beyond which the gravel is not present. This profile seems to indicate a lake-stage twenty to twenty-five feet lower than the maximum level of 375 feet. This spit is on the property of G. E. Taintor.

d 6. A mile and a quarter south by west of the center of Morristown two hills, one of trap the other of Triassic conglomerate, rise to a maximum height of about thirty-five feet above the old lake-level. In the narrow strait separating them, there was laid down a deposit of gravel whose flat surface is now 373 feet A. T., and whose length is about 175 yards. The greater part of this deposit of gravel was derived from the trap hill to the east. The Triassic conglomerate hill at the west supplied comparatively little. The quartzite pebbles from the conglomerate are abundant only where the gravel bed joins the conglomerate hill. A large pit opened in the trap gravel shows that the material is ill-rounded, obliquely-stratified, coarse—the pebbles averaging two or three inches in diameter, but ranging up to eight inches—and more than twelve feet thick. This bed of gravel is on the Spring Brook farm, and is a valuable body of road gravel.

d 7. At the western end of the Triassic conglomerate hill just referred to, there is a deposit of gravel having a rude resemblance to a spit in its early stages of growth This deposit is well exposed along the road in the gravel pits owned and worked by the city of Morristown. The gravel is almost entirely of quartzite pebbles, which have been derived from the hill of conglomerate. They are well rounded, but this is due primarily to pre-Passaic wear. Those pebbles which were broken in the process of disintegration of the conglomerate, show little evidence of wear during their lacustrine history. The upper layers are horizontally stratified, forming the "top-set" beds. Beneath these, the strata are inclined westward towards the end of the spit, forming "fore-set" beds. This structure clearly indicates the method and direction of growth of the spit.

The stratified material certainly extends up to a height of 376 feet,

and possibly a little higher. The surface of the hill at heights much above any possible wave action is strewn with quartzite pebbles, resulting from the disintegration, in place of the Triassic conglomerate. These pebbles are in every respect similar to those found upon the wave-built spit. Beyond the limits of the exposures, therefore, it is impossible to determine positively the extent of the wave-worked gravel. Judging from slight topographic evidence, it probably does not extend higher than 380 feet, and the lake-level was probably 377± feet. The testimony of the three beds of gravel last mentioned, considering both their material and their position, shows conclusively that in this part of the lake the prevailing direction of movement of the shore drift was a little north of west.

In addition to the above deposits, some of which show distinctly the topographic form characteristic of shore features, many other beds of water-worn gravel were found along the shores of the basin at elevations appropriate to wave-built deposits. On Second mountain they occur at a 1,* a 2, a 3, a 4, a 5, a 6, a 7, a 8, a 9, a 10, a 11. On the gneiss highlands at b 2. In addition to those already mentioned on Long Hill, there are others at c 2, c 4, c 5, c 6, c 9, c 10, c 17, c 18, and c 19, and upon the hills near New Vernon they occur at d 2 and d 4. In general the gravel of these deposits is mainly trap, but in a few instances the bulk of the pebbles are shale. The pebbles are, on the whole, poorly rounded. From the character of the gravel, its relation to the underlying terrane, its topographical position and its elevation, there can be no doubt but that the deposits are wave-built.

III. Subaqueous Overwash Plain Bordering the Moraine.

The terminal moraine crosses the lake basin between Summit and Morristown, forming a ridge which in places rises twenty-five to seventy-five feet above the lake-level, but which in other places falls below it. Between Chatham and Stanley there is a break in the moraine a mile and a half wide, in which lies the northern end of Long Hill and the valley of the Passaic river. Along its course across the lake basin, the outer margin of the moraine is bordered by a subaqueous overwash plain of goodly proportions. The especial characteristics of deltas and subaqueous overwash plains are a flat top,

* The location and the elevation of these deposits are shown upon the large map accompanying this paper.

sloping gently from the head to the front, a steep front slope, a lobate margin with deep re-entrant angles and projecting cusps, and a tripartite structure, as seen in vertical sections, consisting of nearly horizontal beds at the top, these underlain by beds dipping steeply towards the front, which in turn rest upon horizontal layers of fine material. (Figure 3.)

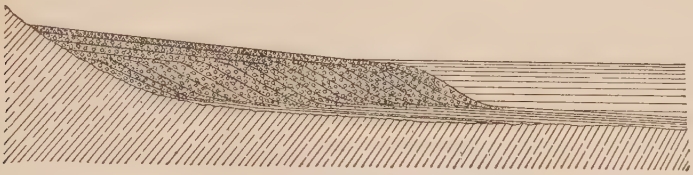

Fig. 3.

Showing structure of delta as shown in cross-section. (Modified from Gilbert.)

Near West Summit there are three prominent marginal lobes on the subaqueous overwash plain. West of Madison, the flat top of the plain is a third of a mile wide, and has a fall of about ten feet, whereas the steep front falls off sixty feet in one to two hundred yards. As will be seen from the accompanying contour map, which was prepared from a careful survey of the plain, the cusps and re-entrant angles are here very pronounced. (Figure 4.) Southwest of Convent station the plain is half a mile wide, declining twenty to twenty-five feet from its

Fig. 4.

Subaqueous overwash plain from Madison to Morristown (southwest of the railway), with a part of the moraine (mainly to the northeast of the railway).

upper edge at the moraine to its outer edge, where it ends abruptly in a steep slope of about fifty feet in 125 to 150 yards.

Kettle holes, varying in size from shallow, saucer-like depressions to huge sinks fifty feet in depth, occur, although such large ones are

not abundant. Travelers on the Delaware, Lackawanna and Western railroad have a fine view of the largest kettle, which lies just west of the track, a third of a mile northwest of Convent station. The railroad runs on this plain from Convent northwestward for a mile or more.

The material varies from very coarse gravel containing large cobbles down to fine sand. Layers of sand are often intercalated between beds of coarse gravel. Lithologically the material is similar to that found in the moraine, and was derived from the melting ice. No exposures were found which showed the complete tripartite structure, nor were there found any extensive exposures showing both fore-set and top-set beds, although one or the other were seen at a number of places.

To fix the exact water-level in which these subaqueous overwash or glacial delta plains were formed, is a matter of considerable difficulty. In a general way it may be said that the line marking the junction of the gently-sloping upper surface of the plain with its abrupt front, marks the water-level. This general statement is certainly very near the truth. But when it is desired to fix the level of the water exactly, or even within two or three feet, it seems to involve many inconsistencies to assume that this line marking the change of slope corresponds accurately with the water-level. There are several reasons for supposing that it does not.

1°. It has been found that even where the change of slope is most marked and can be accurately fixed, its heights vary three, five or even seven feet within comparatively short distances; that is, the line of change from the top to the front is not a horizontal line but a more or less irregularly-curved line. The water could not stand five or six feet higher at one point than it did at another less than a hundred yards away.

2°. But more than this. A consideration of the manner in which a delta is formed shows that the pronounced change of slope must mark the point where the bottom current of the running water which is rolling the coarse gravel along its bed loses its momentum when it reaches the deeper water of the lake. It would seem, therefore, that the steeper slope cannot, at a maximum, be built nearer the surface of the lake than the depth of the current which at that particular spot is supplying debris. Since the depth and velocity of each stream supplying the detritus is different at different points in

its cross-section, and since a subaqueous overwash plain or a glacial delta plain is built by a number of streams or by the distributaries from a single stream, the several streams having various depths and velocities, it is to be expected that the upper limit of the frontal slope will be of various heights on adjoining lobes, and will even vary in height on the same lobe. The conclusion is, therefore, that the lake-level was somewhat (perhaps several feet) higher than the highest of the "fronts," and that the water submerged the outer and lower part of the gently-sloping top. The depth of the submergence at different points would depend on local conditions, but it would never be great.

Just how far above the frontal slope the lake waters reached in the area under discussion is problematical. Its position is not marked by any line on the surface of the plain. It must be fixed rather by the interpolation of data from this and adjacent regions than by any specific mark. On this basis, bringing in data from neighboring wave-cut and wave-built features, it seems probable that (*a*) west of Madison the lake stood at an elevation of about 373 feet, covering nearly all of the plain whose outer edge is 362–5 feet; (*b*) that west of Convent it stood at about 374 feet, the lower edge of the plain being 356 to 364 feet and the upper edge 382 feet; (*c*) that at Morristown it stood at about 376 feet, the greater part of the plain here being but little below this level. Likewise, by the interpolation of data drawn from other sources in the immediate vicinity, it is believed (*d*) that the lake-level at the subaqueous overwash plains near West Summit was at about 367 feet, whereas here the outer edge of the plain is only 345 to 350 feet, from which height it rises gently to an elevation of about 380 feet.

Summary of Shore Features in the Extra-Morainic Basin.

The wave-cut terraces and lake cliffs are in general but poorly developed. In numerous localities ill-defined terraces have been observed at about the supposed lake-level, some of which, by their close connection with more decisive and more definite forms, are probably of lacustrine origin. The best marked of these are upon Long Hill and the gneiss highlands, but, with all possible allowances, it must be admitted that were the proof of the existence of Lake Passaic dependent upon its wave-out terraces, the theory of its existence could not be stoutly maintained. There is not a terrace in the extra-morainic part

of the lake basin the wave-cut character of which, taken by itself, can be said to be entirely beyond question.

The constructional forms are much more satisfactory. In a number of localities there are small but distinctly-formed spits, bars and terraces, whose heights are closely accordant one with another. In many more localities stratified beds of poorly-rounded, but nevertheless of distinctly water-worn gravel of local origin exist, which, although not possessing a distinct topographic form, agree in height, material and structure with the better-defined forms. Where the gravel is not present in beds, scattered water-worn pebbles of local origin have been found at numerous places at the proper levels, and there is good reason to believe that the shore gravel is much more nearly continuous about the lake basin than the surface traces indicate. Nowhere have shore forms, beds of local gravel or scattered water-worn pebbles of local origin been found above the limit at which the waters of the lake could have been confined.

The composition of these gravel beds, considered in relation to the underlying and adjacent indurated formations, is most significant. On Second mountain—a great trap ridge—the gravel deposits attributed to shore action, are composed almost wholly of fragments or pebbles of trap, with only occasional foreign pebbles. The same is true in the main of Long Hill. But on the south side of this ridge the red shale occasionally rises to the former level of the lake. Where gravel beds are found at such points, the shale has made the principal contribution to the gravel. The Durie spit (c 3) west of New Providence is an instance in point. Where the supposed shore of the lake was against a drift-covered surface, the gravel beds are composed of drift gravel. The terrace (c 1) back of the paper mills at Stanley is an illustration. In the vicinity of Basking Ridge deposits of trap gravel grade into those of shale, as the supposed shore line passes the contact of the trap with the shale. Along the gneiss highlands only two gravel beds were found, both of which were largely of gneiss gravel and sand, and local sources for the other constituents are at hand. The gravel deposits on the trap hills about New Vernon are mainly of trap; those on the shale are composed chiefly of shale, and those on the Triassic conglomerate of quartzite pebbles, derived from the conglomerate itself. Waves and shore currents are the only known agencies which can develop beds of water-worn, stratified gravel sustaining this definite relationship to the adjacent and subjacent formations. The presence of

a few foreign pebbles in the gravel is not difficult to explain, but their absence would be. They were derived from several sources. A few may have been transported along the shore from the moraine, or from the ice front, when it formed one side of the lake, by the combined action of waves and shore currents. This would probably apply only to the fresher pebbles found not far from the moraine. Others were probably carried by floating ice to the various parts of the basin. Where the ice melted or grounded near shore, they were incorporated in the shore deposits. The occasional large, fresh-looking bowlders which are now and then associated with these gravel deposits seem by this means to find adequate explanation. At a number of localities about the lake basin, reaching considerable heights above it, deposits of sand, gravel and till are found which present evidence of great age. Beds of drift similar in composition to these and sometimes continuous with them are found within the lake basin. These are believed to belong to the invasion of an ice sheet much earlier than that which formed the moraine.* This pre-morainic drift was a third source of the foreign material found in the shore deposits.

The topographic situation of some of these shore deposits of gravel, taken in connection with their composition, is such as to admit of no second interpretation. Generally speaking, they occur along a horizontal belt at a definite elevation, either (*a*) on the slopes of higher lands, or (*b*) in the passes and cols between them. Above this definite level gravel such as is here described does not occur. Below this level such beds of gravel occur at various points as might have been formed during the later stages of the lake's history, when its level was sinking and its area diminishing. The gravels under consideration were deposited by waves and shore currents. Since they do not occur outside the Passaic basin the waves and currents must have been those of a lake.

There are certain deposits of gravel about the lake basin which are not to be confused with those here discussed. These gravels are so distinct from those of the lake shore, that even the tyro need not be confused in their discrimination.

A careful study of the shore deposits, particularly their relations to headlands of rock and wave-cut benches, gives us some knowledge of the general direction of the waves and shore currents. On Long Hill

*Annual Report of the State Geologist of New Jersey for 1891, pages 102–111; 1892, pages 60–72.

the shore drift traveled in general southwestward, as is shown by the high terrace near Stanley (c 1), the Durie spit west of New Providence (c 3), and the spit northeast of Gillette (c 7). On Second mountain a general direction cannot be made out. Some of the deposits, notably the one south of Union village (a 2), were derived from the southwest; others are found to the west or southwest of the sources of supply. Near Basking Ridge the material was carried southward, as shown by the red shale deposit south of the depot (c 16), and the trap gravel at the south end of the ridge near Lyons (c 15). The three deposits (d 5, d 6 and d 7) a mile and a half south of Morristown were clearly formed by westward-moving currents.

Three particularly favorable classes of localities for deposition can be made out. These are—1°, in the shallow, narrow straits between islands, the numerous deposits along Long Hill being the most marked examples; 2°, at the ends of islands or peninsulas where the shore currents (*a*) kept their course and velocity as the island was passed, spits being the result, the Durie spit west of New Providence (c 3) being a good example; or (*b*) where the shore currents lost their velocity by spreading, in which event terraces were formed; the terrace just north of Lyons station (c 15) may serve as an example; 3°, at the heads of small converging bays, where terraces of considerable extent were sometimes formed. The terraces west of Basking Ridge (c 16), east of Bernardsville (a 12), and a mile and a quarter northwest of New Vernon (b 2), are good examples. Other instances may be seen upon the large map accompanying this paper.

Finally, the subaqueous overwash plain along the whole outer margin of the moraine so far as it lies within the lake basin, is indisputable evidence that a large body of standing water once occupied the low ground to the southwest, the height to which it rose being approximately marked by the outer edge of the gently-sloping upper surface of the plain. The depositional shore features of the extra-morainic part of Lake Passaic are therefore regarded as demonstrative of its existence in this part of the basin. In view of this demonstration, much weight may be attached to the possible wave-cut terraces and accompanying cliffs heretofore described.

The extent to which most of the extra-morainic constructional features of the lake are developed, and they still retain essentially their original form, is so moderate that the conclusion seems certain that the history of the lake was a brief one. The spits, for the most part,

are no more than well started. The terraces are narrow and often ill-defined. The beds of gravel are nowhere very thick or extensive. The very considerable subaqueous overwash plain along the moraine might be of very rapid construction, so that a long period of time is not demanded for its growth.

Deltas in the extra-morainic part of the lake.—Apart from the glacial drainage, the streams which emptied into Lake Passaic were generally small and short. Those on Second mountain could not have been more than a mile long. On the gneiss highlands they were larger, but nevertheless were of slight importance. Whippany river was probably the largest of these. Careful search failed to show any traces of deltas at the mouths of any of these streams. The Whippany valley, from Morristown to Brookside, was examined with great care. This valley was either filled by an independent lake, if the ice blocked the mouth of the valley at Morristown, or by an arm of Lake Passaic. No traces of shore lines are to be found, nor were any remnants of a delta observed.

The absence of fossil deltas, not only here, but at the mouths of all the tributaries to the lake, seems to substantiate the conclusion reached from other lines of evidence that the lake was short lived. The drift supplied by the streams was not more than could be handled by the waves and incorporated in the shore drift.

B. INTRA-MORAINIC PORTION OF THE BASIN.

The intra-morainic portion of the Passaic basin differed from the extra-morainic in certain essential features. Since it was occupied by ice for a portion of lacustrine time, its lake history, if such there was, must have been briefer than that of the extra-morainic portion. If shore features were formed in the interval between the closing of the pre-glacial outlet and the advance of the ice to the line of the moraine, they stood good chance of destruction by the ice as it advanced to its extreme position. Only those shore features which were formed after the ice retreated from the moraine, and before the old outlet across the trap ridges was re-opened, could be expected to remain. In so far as this period was shorter than that of the lake as a whole, we should expect the shore features to be less strongly developed than outside the moraine. On the other hand, since the glacier left thick deposits of sand, gravel and till on the sides of the basin, upon which the

waves could readily work, and since an enormous amount of loose material was furnished to the waves directly from the melting ice, constructional terraces, spits, bars, etc., could have been rapidly constructed under these favorable conditions. The abundant supply of shore and glacial stream drift might even more than compensate for the short life of this part of the lake.

There is another and essential difference between the two parts of the lake basin. Since the ice filled the intra-morainic part of the basin, and covered all the surrounding country, deposits of more or less rounded and water-worn gravel are liable to be found at any and all elevations. The mere presence, therefore, of such deposits, even at elevations accordant with the shore lines, cannot be regarded as evidence in favor of the existence of the lake. Unless they possess the structure and the topographic forms characteristic of shore deposits, they cannot be of value in the present discussion. With these general considerations in mind, the possible shore features of this part of the basin may be considered in detail.

I. Possible Wave-cut Terraces and Lake Cliffs.

On the inner face of the moraine between Chatham and Littleton there are discontinuous terraces in the drift, often of considerable width. In places they are bowlder-strewn, and limited above by sharply-defined cliffs. These benches belong to two sets of elevations—the one fourteen to eighteen or even twenty feet lower than the other. The upper is generally the most sharply defined, and has the steeper cliff. It is well shown at the southeast end of the high hill between Morristown and Littleton (F 5), and also south of Monroe (F 3). The lower set is developed midway between Chatham and Madison (F 1), between Convent and Madison (F 2), and also northeast of Morristown (F 4). These are probably lacustrine in origin. The width (100 to 300 yards) of these terraces on the inner face of the moraine is considerable for so small a lake, and for one having so brief a history. But there were several favoring conditions for their rapid development. The waves worked upon incoherent materials, largely sand and gravel. The terraces are so situated as to have been exposed to a considerable sweep of waves, particularly towards the later stage of the lake period, when the ice had almost withdrawn from the lake basin; and finally, when waves cut a terrace upon a

gently-sloping shore, the lower edge of the terrace may pass almost insensibly into the original slope, and so the width of the wave-cut portion may seem to be much greater than it really is. It is quite probable that only the shoreward parts of the above terraces are really wave-cut. On the eastern shore of the lake, between Summit and Caldwell (H 1, H 2), particularly east and southeast of Livingston, benches have been observed which in some respects resemble wave-cut terraces. Even if lacustrine, they can hardly belong to the maximum stage of the lake. Elsewhere, save a doubtful case on Riker's hill (K 1), no benches were observed which can be regarded as lacustrine. These possible wave-cut terraces would in themselves be an insufficient basis for affirming the existence of a lake in the intra-morainic part of the Passaic basin. Taken in connection with other lines of evidence to be hereafter adduced, the foregoing terraces have corroborative value.

II. Constructional Shore Features Within the Moraine.

On the moraine.—f 1. During the lake period the high hill midway between Littleton and Morristown formed the northern headland of a curving bay a mile in width. At the head of this bay is a small, wave-built terrace, sloping gently to the southeast, and connected with higher ground to the northwest. Its upper limit is 375 feet, and its lakeward slope is eight or ten feet in a hundred yards. A few hundred yards east of this terrace is a spit two hundred yards long, forty yards wide at its free end, but increasing in width northward to its junction with a wave-built terrace, which rapidly passes into the wave-cut terrace at the south end of the hill.

Fig. 5.

Spit on the face of the moraine midway between Morristown and Littleton. Scale three inches to one mile.

The spit rises eighteen or twenty feet above the low ground around it. At its free end the height of its surface is 369 feet, which increases to 378 feet at its upper limit. This spit (Figure 5) is on the property of John Pearson. The material, as is the case in all the constructional shore features of this half of the lake, is glacial sand and gravel.

f 2. Just west of the three corners, half a mile south of Littleton, is a flat-topped spur of sand and fine gravel, having an elevation of 382 feet. Its form strongly suggests a lacustrine origin. Its height, and its close association with the wave-cut terrace along the side of the hill to the southeast, give weight to the suggestion. The association of these two spits with the wave cut terrace, the first (f 1) at the southwestern end of the terrace and the second (f 2) near its northern end, is a characteristic combination of shore phenomena.

f 3. A mile northeast of Littleton, along the road to Boonton, is a gently-undulating plain of sand and gravel, containing some bowlders, and passing, at its upper edge, into the moraine. The elevation of this plain is about 380 to 385 feet, and although its form does not point positively to a lacustrine origin, it may be that it is the result of the combined cutting and building action of the waves working upon stratified drift.

On the gneiss highlands.—g 1. A mile north of Parsippany there is a gently-sloping, slightly-undulatory plain of sand and gravel, having an area of a quarter of a square mile. It has the lobate margin, steep front and re-entrant angles, characteristic of a glacial delta, *i. e.* a delta formed in standing water in immediate connection with the ice, the detritus being supplied by a glacial stream. The lobes of this glacial delta rise abruptly thirty feet above the lower land to the south and west. Northward the plain passes into an irregular kame area, the site of which, it is believed, was occupied by the ice during the formation of the delta. To the south there are a number of large kames, which were probably formed before the ice had retreated to the kames north of the plain, and which, therefore, antedate the plain. The southern limits of the plain seem to have grown out to, and to have partly encroached upon the nearest of these kames. The general level of the plain is 396 feet. The ends of the lobes vary from 390 to 394 feet. From these figures the water-level would appear to have been about 394 or 395 feet. The kames south of the plain must therefore have all been submerged during the maximum lake stage. On some of them, traces of terraces at about 362 feet were observed, although they were not very definite.

g 2. Between Boonton and Montville, southeast of the canal, there is another glacial delta having an average width of three-eighths to one-half a mile, and a length of two miles. The surface is gently undulatory but perhaps not more so than is possible for a plain built

in immediate connection with the ice front by a number of streams of varying velocities and volumes. The ice, too, may have co-operated, at least passively. The height of the outer margin of the plain at the top of the steep frontal slope varies between 381 feet and 399 feet, with variations of ten or twelve feet within thirty rods or less. In general, however, there is a rise of the margin towards the northeast. The general level of the plain is under 400 feet, and the water-level, so nearly as it can now be determined, was about 394 or 395 feet at the Boonton end, and probably a little less than 399 feet at the Montville end. Towards the upper limits of the plain, near the canal, bowlders become more numerous and the surface is more irregular. Patches of till are also present, apparently indicating that the ice lay on the higher ground to the northwest during the formation of this delta plain. If this were the case the general slope of the surface of the plain would be away from the ice towards the lake, and the internal structure should have a lakeward dip.

A single small pit was found on the Boonton plain, which showed that the beds at that point dipped northward, nearly opposite to the direction which would have been expected, if the plain was built from the northwest as supposed. But it is unwise to assume that this is the normal dip for all the beds, or indeed that it is the usual direction of dip. Particularly is this true since other features of the plain, *i. e.*, for example, its surface slope and its lobate margin, and the unmistakable structure of neighboring plains, all agree in the supposition that the ice lay upon the high land to the northwest, and that the plains were built from the edge of the ice outward into the lake. The difficulty presented by the direction of dip at the observed exposure may be met hypothetically as follows: If the plain was built around and over a number of pre-existent kames, its surface might be more or less hummocky provided the kames were not completely buried. In this case the internal structure of the plain might be more or less confused and discordant, as the material was washed irregularly into the depressions between the kames. Besides this, the beds of a kame might dip steeply in a direction opposite to the general dip of the beds of the delta plain proper, and a single small excavation might reveal only the kame beds. From such an exposure it might seem that the plain had been built towards the highland, after the manner of a terrace formed in the angle between the side of a valley and stagnant ice occupying the low ground, even though

this was not the fact. If this were the case the general dip of the beds would be towards the hillside if the material was derived from the melting ice.

The lobate front of the Boonton delta plain is well developed, the projecting lobes being sharply defined, falling off steeply fifty to seventy feet. The re-entrant angles also are clearly marked. Post-lacustrine erosion has in some cases undoubtedly increased their distinctness, but at many points they seem to preserve essentially their primitive forms. Along much of the front of this delta plain, there is a lower terrace, the height of which is about 320 feet (hand-level). At various other points along the lake margin, a series of terraces about seventy feet below the maximum shore line have been observed. These will be mentioned in their appropriate geographical position, but their exact relationship to the higher terraces, structurally and chronologically, will not be discussed until the history of Lake Passaic is considered.

Fig. 6.

Topographic map of the Montville delta. Scale three inches to the mile. Contour interval 10 feet.

§ 3. Just north of Montville there is as perfect an example of a glacial delta as could be desired. It is represented in contour in Figure 6. Its area is about a quarter of a square mile. Its surface is nearly flat save for an occasional shallow, saucer-like depression, and a gentle slope from north to south. Its distinctly-marked lobes rise seventy to ninety feet above the irregular kame areas toward the south. The Delaware, Lackawanna and Western railroad skirts its southern edge at the foot of the lobes, cutting directly across the end of the southernmost projection. The upper fifty feet of this section shows cross-bedded sand and gravel dipping towards the end (south) and sides of the lobe. This exposure is so large that there is no hesitation felt in asserting that this lobe and the delta of which it was a part, were built from the north. Beneath this fifty feet of gravel are one to six feet of clay and fine sand. The laminæ of the clay are thin, one-eighth to one-sixteenth of

an inch in thickness, and separated by thin sandy partings. As seen in the section the clay and sand layers are horizontal, but they may have a slight southward dip. The clay, to all appearances, is exactly similar to that found at numerous low places in the lake basin, and regarded as undoubtedly lacustrine. Towards the sides of the lobe, the clay layer is succeeded by coarse sand and gravel stratified parallel to the side slope of the present surface. Beneath the clay there is more sand and gravel, the fine sand being stratified horizontally, the coarse materials irregularly bedded as in a kame. The coarse, irregularly-bedded gravels probably represent a kame, around and over which were deposited the finer materials supplied by the glacial drainage which entered the lake half or three-quarters of a mile to the north. In time, the margin of the lake was so filled up by the coarser materials deposited nearer shore, that the streams came to drop their coarse material farther out on top of the fine deposits, made at an earlier time. Since there are no stratified deposits on the slope of the hill north of the delta plain, and since the slope of this hill shows no signs of river channels cut in the till, the conclusion is that the streams which built this delta were short, and that the edge of the ice was very near the head of the plain.

The heights of the margins of the different lobes vary from 388 to 395 feet, and the plain ascends gradually to a height a little above 400 feet. The water-level seems to have been about 397 or 398 feet. On one of the lobes there is a faint indication of a terrace at about 325 feet, but no corresponding signs were found on the others.

Across the road just west of the northern end of this plain there is a small lobe whose height corresponds very closely with that of the larger plain. This may properly be considered as a part of the larger plain isolated in construction, and further separated by erosion.

g 4. Half a mile northeast of the Montville delta is a small and not very well-defined terrace, which may have been built in standing water. It is more or less kame-like in places, and its origin is not certain. If it is to be referred to the lake, which may be fairly questioned, it seems to indicate a stand of the water at about 370 to 380 feet. There is also a faint indication of a terrace on the northeastern side of the Montville delta, at about the same level.

g 5. With the above exceptions there are no traces of shore lines in the first two miles northeast of the Montville delta, but at the three road corners, a mile and three-quarters north of Whitehall, there is a

small and well-formed glacial delta, represented in contour in Figure 7. This may be called the Jacksonville delta, from its proximity to the Jacksonville school-house. In some respects this delta is the most significant in the lake basin. The top has very little slope until the brow of the lobes is reached, where there is a quick change, and on the south an abrupt fall of fifty feet. Northward, towards the head, the surface becomes slightly undulatory, and at length breaks up into low kames north of the sink represented in the figure. The northern margin of the delta plain is marked by wide re-entrants between which are narrow, cusp-like lobes of gravel and sand. The slopes are kame-like and bowlder-strewn. The limit of the bowlders towards the front of the delta is nearly coincident with the limit of undulations of the surface, although an occasional bowlder is found

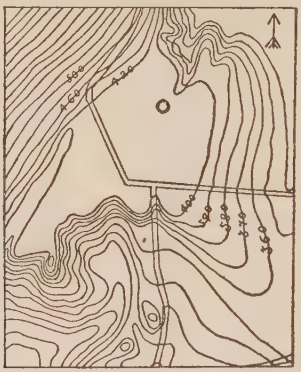

Fig. 7.

The delta near Jacksonville school-house, one and three-fourth miles north of Whitehall, shown in contour. Scale three inches to the mile.

upon the plain proper. The topography of the head of the delta makes it clear that the ice stood at this point while the delta was being formed, and that when the ice melted, the head of the delta was left unsupported, and the sand and gravel slipped and settled down irregularly.

It is only for a narrow strip on the northwest side that the delta abuts against higher ground. Directly south of the delta front are a number of kames which just escaped burial beneath the advancing delta. The heights of the crests of the different lobes are 408, 407, 406 and 398 feet, the lowest lobe being as clearly and sharply defined as the higher ones. The general level of the plain is about

410 feet, and the height of water must have been between 408 and 410 feet.

No lower terraces were found upon the slopes of this plain nor upon the slopes of the neighboring kames.

g 6, g 7. At two points (g 6, g 7) between the Jacksonville delta and Pompton there are topographic forms, which are referred with some doubt to the lake. The more important of these (g 6) is a terrace (335 to 340 feet, hand-level) traceable for nearly a mile, with a width of 100 to 150 yards. This terrace possesses certain features which suggest that it was formed in the angle between the gneiss highlands and stagnant ice occupying the valley, the material being supplied by the ice. On the other hand, its height accords fairly well with that of the faint lower terraces near Boonton and Montville, and in so far as this is any criterion of its origin, it is favorable to the lake hypothesis. In no event can it be referred to the maximum stage of the lake.

North of Pompton no traces of shore lines were observed, nor were any seen upon the trap hills on the east side of the Pompton plains. This is to be expected, since by the time the ice had melted back as far as Pompton the outlet at Paterson would probably have been open.

On and near Second mountain.—Shore features are not so well developed on the eastern shore of Lake Passaic as on the western, but there are enough to make it possible to fix the position of the shore line with some accuracy.

h 1. At Upper Preakness is the largest and most typical glacial delta plain found within the lake area. Its surface is nearly flat. Its margin is strongly lobate, falling off abruptly fifty to fifty-five feet. Its area is about a square mile. Its altitude at its front is from 330 to 335 feet, from which elevation its surface rises gradually for nearly a mile, to 360 feet. To the northwest, the plain abuts against a strongly-marked kame area, the knolls of which rise to 420 feet. On the northeastern side, the plain falls off very abruptly eighty feet, into a swamp. The margin here presents, to a slight degree, the concave, steep, and billowy appearance characteristic of deposits built against an irregular ice front. The material of which the plain is built varies from fine sand to coarse gravel and cobbles, but bowlders are uncommon, or altogether wanting.

Just north of this plain is a moraine-like kame belt half a mile in

width. The hillocks are of coarse material, and in general thickly strewn with bowlders. During the time that the Upper Preakness delta was being built by glacial streams, which flowed into a lake whose waters stood at a height of between 335 and 340 feet, the kame belt would seem to have been forming just beneath and at the irregular margin of the ice. A large ice mass perhaps occupied the area of the swamp just north of the plain.

h 2. North of the kame belt is another but more irregular plain of sand and gravel. While it was probably not fashioned entirely beneath water, and perhaps not principally, its surface still seems to have been more or less modified by the action of standing water. But this is not beyond question; to have extended over it, Lake Passaic must have had here an elevation of about 412 feet. The surface of this plain is not strewn with bowlders, and in this respect it is in marked contrast with the half-buried moraine-like kames, which, near its southern margin, rise above its surface. The evenness of the surface of the plain is broken by numerous sinks and hollows, which may find a partial explanation in the unequal settling of the sand and gravel due to the melting of blocks of ice incorporated in the sand and gravel of the plain during their deposition. The height of this plain accords with the height of the Jacksonville delta, while that of the Upper Preakness plain corresponds to the terraces near Pompton, and the lower benches near Boonton and Montville. The relationship of the 412-foot plain to the moraine-like kame area, on its outer margin, is such as to strongly suggest that it was formed after the lower plain at Upper Preakness.

h 3. On the slope of Second mountain, one and a half miles west of Haledon, there are terraces at two levels, the upper marking a water stage of 405 ± feet, the lower, one of 340 feet. In places the lobate delta margin is well developed, falling off steeply thirty to forty feet. These terrace plains are closely associated with kames, some of which rise steeply above the surface of the plain, while others are partially buried near the outer part of the plain. The surface of the kames is marked by many bowlders, whereas they are very rare upon the surface of the terraces. The terraces are composed of sand and fine gravel. Here again we seem to have a kame area, probably formed between or beneath the ice, as shown by the bowlders on its surface, and which was afterwards partly buried by the sand

and gravel of a glacial delta, formed when the ice had retreated a short distance from the kame belt.

Traces of the higher plain were noted between the kames further north, toward the higher plain north of Upper Preakness, but they are not distinct. The relationship in time of the higher terrace to the lower, where they are both present, will be considered later.

h 4. There are no shore lines along the trap ridge between the terraces west of Haledon and Caldwell, a distance of seven miles, unless a small, spit-like form, half a mile north of Cedar Grove, having an elevation of 375 feet, is to be regarded as such. In the vicinity of Caldwell there is a somewhat extensive sand and gravel plain, whose evenness and regularity are more or less interrupted by kames and ravines. Those kame hillocks whose summits are of about the same height as the plain are somewhat flattened, as if more or less truncated by the waves. The plain is well developed near the school-house and cemetery of Caldwell, where its height is 385 to 387 feet. It rises towards the east, being about 410 feet at the Presbyterian church, half a mile east by south of the school-house. This plain indicates a lake-level of 385 to 390 feet.

In front (northwest) of the school-house and cemetery, this higher terrace falls off somewhat abruptly to a lower one, whose average height is about 363 feet, and whose width is from 150 to 200 yards. Half a mile north by west of the church, this lower terrace is better developed, its outer edge being 358 $\pm$ feet in altitude, and its upper margin 369 feet. Above it there is an indistinct bench at an elevation of about 400 feet. In front of the school-house, the outer margin of the lower terrace is more or less delta-like, and falls off steeply forty or fifty feet.

The higher plain (393 $\pm$ feet) about Essex Fells, one mile southwest of Caldwell, is a continuation of the upper part of the school-house level, while the poorly-defined level west of the depot at Essex Fells is about 360 feet high, and appears to correspond to the lower terrace at the school-house. Numerous pits have been opened in the kames about Caldwell, but there are no large exposures showing the structure of the plain surrounding the kames. The thickness of the stratified gravel is very great. A well near the school-house was sunk 120 feet, and one near Essex Fells station 145 feet, neither of them reaching bed rock.

h 5. A mile south of Roseland a small terrace was noted on the

slope of Second mountain. Its height is about 370 feet (hand-level), and it may be wave-built in origin, but no positive assertion can be made to this effect. At one or two other places, also, between Caldwell and Summit, faint traces of what might be wave-built forms have been seen.

On islands.—k 1. Near the northern end of the trap hill west of Livingston is a small deposit of gravel, largely trap, poorly waterworn and strongly resembling the trap gravel beds of the extra-morainic portion of the basin, save that there is a larger percentage of foreign pebbles. This deposit, which, where exposed, does not exceed five feet in thickness, lies between two hills of trap, which must have been islands in the lake. The height of the gravel bed is 378 feet (hand-level), agreeing very closely with the spit and wave-cut terrace northeast of Morristown, due west across the lake. This may probably be referred to the lake waves, although it is possible that it might have been formed beneath the ice.

k 2. Again on Hook mountain, half a mile northwest of Horse Neck bridge, is a small, spit-like deposit of fine gravel. Its entire length is less than 100 yards, and its upper edge has an altitude of 386 feet. Other than this rather indefinite feature, no traces of shore line could be found upon Hook mountain.

Within the area of the lake, there are many hills 250 to 360 or 370 feet high. Some of these are of sand and gravel, others of till, and still others seem to be mainly of sand and gravel more or less thickly veneered with till. Careful search failed to show any unmistakable shore features upon the regular slopes of these hills. This indicates the rapid final draining of the lake, a point which will be discussed later.

Summary of the shore features within the intra-morainic basin.

In that part of the lake basin lying within the moraine, the chief constructional shore features are glacial deltas, built in immediate juxtaposition to the ice, by heavily-laden glacial streams. Under these conditions the supply of material was great, and the growth of the deltas rapid, resulting in the production of very considerable plains, in a comparatively brief time.

These glacial deltas are numerous and decisive in character. They occur in greater numbers and better development on the west and

northwest side of the lake than upon the eastern shore. In one case at least, these deltas were built out into water seventy to eighty feet deep, and depths of forty to fifty feet are common. The plains north of Montville, west of Jacksonville school-house, and at Upper Preakness are the best examples.

In the two last-named cases, the northern margins of the deltas show the irregular form and the hummocky surface slopes characteristic of gravel beds which were originally built against the ice, and which have since slipped and fallen down as the ice melted, though retaining in part the irregularities of the ice mould in which they were cast. Several of the other plains pass into kame areas which are believed to have been formed beneath and at the irregular edge of the ice, and to mark the position of the ice front, at the time of the formation of the glacial deltas. The surface of these kame belts is often strewn with bowlders, in marked contrast to the surface of the associated delta plain. In a number of cases, kames of an older generation have been partially buried by the advancing front of the growing deltas. This is true of the Caldwell area particularly.

The only delta in which the structure is well exposed is that north of Montville, where the railroad has cut across the end of one of the lobes. Here the outward dipping, fore-set beds are clearly shown, underlain by horizontal deposits of fine sand and clay. At the bottom of the exposure, near one end, there is an irregularly-stratified body of coarse gravel and sand, which is believed to represent the surface of a buried kame.

In addition to the highest shore line indicated by the tops of all the glacial deltas except the Upper Preakness plain, two indistinct lower levels can be made out in several places. One of these is about twenty feet, the other between sixty-five and seventy-five feet below the highest. The time relationship of these inferior levels to the maximum will be considered later.

In addition to these glacial deltas there are a few small spits connected with what appear to be wave-cut terraces, and a few kames whose summits seem to have been somewhat truncated by the waves, but aside from the glacial deltas the wave-built forms are not conspicuous or decisive.

As in the extra-morainic portion of the lake, the constructional shore features are much better developed than those fashioned by the destructive action of the waves. They are so numerous, and on the

whole so distinct and so harmonious, that in themselves they constitute proof that the intra-morainic portion of the Passaic basin was occupied by standing water for a length of time sufficient for the accomplishment of the observed results. If the intra-morainic shore features seem disproportionately prominent when compared with the extra-morainic, it must be remembered that the conditions were far more favorable for the development of constructional shore features within the moraine than without, since in the former area the waves beat upon incoherent drift, while in the latter, except for the thin coating of residuary material, they beat upon solid rock Deltas are the most conspicuous intra-morainic shore features. For the formation of deltas outside the moraine there was little opportunity. The largest deltas within the moraine may well have required far less time for their building than the gravel beds along the trap ridges for their accumulation.

THE LACUSTRINE DEPOSITS OF LAKE PASSAIC.

A. IN THE EXTRA-MORAINIC BASIN.

Iceberg deposits.—Iceberg deposits in the extra-morainic portion of Lake Passaic were discussed briefly in the Annual Report of the State Geologist of New Jersey for 1892.* Later field-work by the author failed to bring to light any further facts concerning them. They consist mainly of bowlders similar to those of the moraine, and are found frequently up to altitudes of 340 feet, and more rarely up to the maximum level of the lake. Although distributed more or less frequently over all the basin, they are particularly conspicuous on the low ground in the immediate vicinity of the Moggy Hollow outlet west of Liberty Corner.

In the vicinity of New Providence, Berkeley Heights and Union Village there are considerable deposits of drift which at one time were thought to be possible berg deposits. But since a tongue of ice probably extended beyond the moraine, down the narrow valley between Second mountain and Long Hill, this drift was more probably deposited by this means. This drift, however deposited, bears the marks of subaqueous deposition, or of submergence subsequent to its

* Page 136.

deposition. It is believed to be till, subsequently covered by the waters of the lake.

As was stated in the Annual Report of the State Geologist of New Jersey for 1892,* "bowlders of granite, gneiss, quartzite and conglomerate are sometimes found above the probable shore line on the trap ridges." As compared to the bowlders of corresponding material below the shore line, their greater age is shown by their greater decomposition. They are regarded as a part of a pre-morainic sheet of drift.

Lacustrine silts and clays.†—Clays and silts, which are believed to be lacustrine, have been observed at various points, and seem to occupy most of the low areas of the extra-morainic basin. They extend from Green Village, Pleasantville, and Logansville on the north, to the foot of the northern slope of Long Hill on the south, and to the foot of the subaqueous overwash plain on the northeast. They therefore underlie all the area of the Great swamp and the surrounding low ground. Within this area they do not occur above an altitude of 240 feet.

The clay of the eastern half of this area, as far west as the road from New Vernon to Gillette, is covered with fine sandy loam, which, east of the longitude of Green Village, changes into sand and gravel. Clay more or less buried by stratified drift which is continuous with the subaqueous overwash plain, has also been found south of Morristown, on the banks of the brook southwest of Convent, and at the bottom of deep wells southwest of Madison.

There seems good reason for believing that the ice during an advance, just preceding the formation of the moraine, extended at least as far as Green Village, forming the kame-like mounds of sand and gravel ‡ which in that vicinity overlie the lacustrine clay. The fine sandy loam met with farther west, is probably contemporaneous with these gravel knolls. This relationship shows that the lacustrine clay antedates the maximum advance of the ice, as will be seen later. The age of the clay is of great importance in interpreting the history of the lake.

The clay in the Great swamp area attains considerable thickness. In general, artificial excavations do not reach its bottom, except where

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* Page 137.

† Annual Report of the State Geologist of New Jersey for 1892, pages 137–140.

‡ Annual Report of the State Geologist of New Jersey for 1892, page 86.

it is very shallow. Wells twenty-five or thirty feet deep do not pass through it, except along the edge near the higher ground. It is known to attain a thickness of over a hundred feet in at least one locality,* a mile and a half south of Green Village, although there is no positive evidence that all this clay is lacustrine.

Although the clay in the Great swamp area does not extend higher than 240 feet, similar clay has been observed at greater elevations outside the swamp. At the clay pits south of Morristown it has an elevation of 310 to 320 feet. Here it is overlain in places by two to three feet of stony clay which closely resembles the clayey till in the vicinity of New Providence and Union Village. Fresh, glaciated cobbles and bowlderets of slate, limestone, gneiss, Green Pond mountain conglomerate, and trap are contained in this stony clay. A few glaciated pebbles were noted well down in the lacustrine clay. The stony clay is not separated from the underlying lacustrine clay by a sharp line, but passes into it by a transition layer of no great thickness. Here again the relationship is such as to indicate that the lacustrine clay antedates the maximum advance of the ice.

A mile southwest of Convent station, lacustrine clay, beneath a layer of stratified sand and gravel, is exposed along the brook near the Spring Lake Company's ice house. The clay has an elevation of 270 to 280 feet. The sand and gravel is closely associated with the lower margin of the subaqueous overwash plain. Here the brook has not cut more than fifteen feet in post-lacustrine times.

Again, three miles south of Morristown, near the red shale gravel deposit (d 4), on the property of Mr F. F. Lippman, lacustrine clay is exposed along the road for 175 yards to a maximum depth of eight feet. Its vertical range is from 315 to 345 feet. This clay is somewhat stony, containing pebbles of red shale and trap. In this respect it differs from the clay at low levels, which rarely contains stony material. This is the highest point at which lacustrine clay, or clay apparently of lacustrine origin, has been noted.

Between Second mountain and Long Hill, along the Passaic and Dead rivers, there is considerable clay. It does not reach elevations higher than 220 or 225 feet. In appearance it is similar to the clay of the Great swamp area, but it has not been shown to antedate the morainal accumulations. Indeed, as will be seen later, some of it at least probably belongs to the closing stages of Lake Passaic.

* Annual Report of the State Geologist of New Jersey for 1892, page 139.

The lacustrine clay at the lower levels is "fatty or greasy," and a little below the surface is finely laminated, the thin laminæ of clay being separated by fine partings of a more sandy nature. It is calcareous, much more so than the adjacent portions of the moraine.

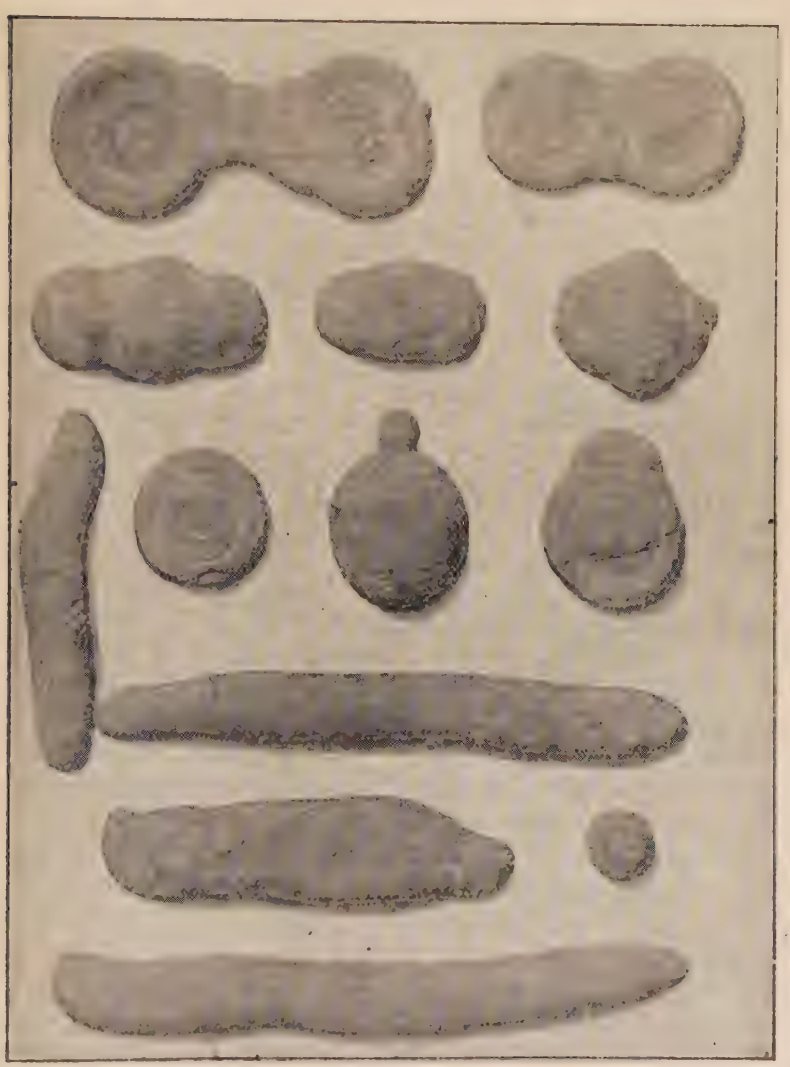

Fig. 8.
Calcareous concretions from the lacustrine clay. About two-thirds natural size.

It frequently contains concretions of carbonate of lime. These concretions are very abundant in certain layers of the clay. They sometimes occur in clumps in certain horizons rather than being regularly distributed. They have their flat sides parallel to the layers of clay. In shape they are curious and varied, ranging from slender cylinders five or six inches in length, and half an inch in diameter, to perfect spheres and round disks. Many of the disks are double, roughly resembling a pair of eye-glasses, and showing a marked degree of symmetry. The accompanying figure shows a number of typical forms taken from a well at a depth of twelve to twenty feet, on the farm of Mr. A. H. Baird, Pleasant Plains. Similar concretions occur in the clay pits south of Morristown.

In addition to the evidence drawn from the shore features, the berg-dropped bowlders and the lacustrine silts and clays, there are other facts, or series of facts, which possess a corroborative significance. When compared with the residuary soils above the shore line, the soil and subsoil covering the trap ridges below this line often possess slight but significant differences. These differences were noted more particularly on the gentle slope of Second mountain, although they are not always discernible even here, and they were occasionally conspicuous elsewhere. The difference is shown in several ways—(1) In addition to the fresh-appearing foreign bowlders dropped by icebergs, trap pebbles, which have the appearance of wear, either because of partial rounding or by reason of freshened surfaces due to the removal of the weathered outer layer, are somewhat widespread. This is true even where there are no beds of shore gravel. (2) The trap pebbles are frequently contained in a clayey matrix, somewhat unlike the unmodified trap residuary clay. The exact difference is difficult of definition in words, but less difficult of recognition in the field. In general, the matrix seems more compact below the lake level, and the pebbles seem to be set in it somewhat differently. Below the lake-level, too, there is not the same transition from greater to less oxidation from top to bottom as in the most typical residuary deposits. In many cases this re-working of the trap residuary is very slight, and the differences in appearance are not obtrusive. In some cases, careful search reveals the presence of a few foreign pebbles along with those of trap origin, in the matrix of clay. So far as observed, these characteristics are limited to the trap soils below the shore line and are not found in the trap residuary above that limit.

In many places, also, the soil on the red shale within the lake basin possesses a waxy, clayey nature, not characteristic of unmodified red shale residuary. This waxy character is what would be expected in a shale residuary soil which had been submerged and more or less reworked beneath the lake. In the case both of the trap soil and the shale soil, it is not easy to assert, positively, that these changes are due to lacustrine conditions rather than to any other, but since, so far as observed, they are limited to the lake basin and do not occur above the shore line, it is a rational inference that they are due to the lake.

B. IN THE INTRA-MORAINIC BASIN.

Iceberg deposits may have been formed in this part of the lake basin during the period of ice advance, before the glacier reached the limit now indicated by the moraine, and also during the period of ice retreat. The earlier deposits must have been overridden afterwards by the ice, and more or less buried by the later deposits formed in direct connection with the ice. It is, therefore, extremely improbable that any of this theoretical early berg till is anywhere exposed in the lake basin, or, if exposed, that it could be recognized. Berg deposits formed during the retreat of the ice may be present, but their discrimination would be very difficult, and in the majority of cases impossible.

Clays which are of the lacustrine type have been observed at several localities within this part of the lake basin. They are finely laminated, with thin partings of very fine sand. Like the extra-morainic lacustrine clays, they are waxy or greasy, more or less calcareous, and contain concretions similar to those found in the lacustrine clays of the Great swamp area. These clays are generally at low levels, and are associated with clays which may be post-glacial in origin. Such are the clays found in the marshes along the Whippany river. Brownish-blue clay, which is probably lacustrine, was noted on the hill midway between Whippany and Hanover, at a height of 230 feet—sixty feet above the river and marshes. Here it is overlain by several feet of stony, clayey till. North of West Livingston there is a low area, having an altitude of 200 feet, which seems to be covered with lacustrine clay, but there were (1893) no good exposures by which this point could be tested. Similar clay, containing concretions, is exposed on the right bank of the Rockaway river, a mile

and a half northwest of the south end of Hook mountain. Here the river has cut through a thin coating of glacial sand and gravel into the underlying clay. Between Little Falls and Mountain View and north of the latter place there is considerable clay which, where exposed in pits, is of the lacustrine type. It is all at low levels, 170 to 190 feet, and is overlain by stratified material and in places by till. At one of the largest of these pits, half a mile north of Mountain View station, the laminæ of the clay are sharply crumpled and contorted into anticlines and synclines two to three feet in diameter. The crumpling is best marked in the upper layers, although all exposed layers, ten feet or so in thickness, are affected by it. The axes of these folds extend, as nearly as could be determined from the exposures seen, from northeast to southwest, or roughly speaking, parallel to the direction of glacial movement. The clay in this pit is overlain by six or eight feet of glacial sand, which is contorted very similarly to the clay, and which contains a few cobbles. The cause of this contortion is not known. Since many of these clays are covered, locally at least, by till, they would seem to belong to an early period of the lake's history, if they are lacustrine at all.

In addition to the lacustrine clays, there are certain peculiarities of the glacial drift in parts of the lake basin which may be due to lacustrine conditions.* In brief they are as follows: Between Parsippany and Madison, and eastward to the Passaic river, a thin but variable layer of till covers a great depth of sand and gravel. Over considerable areas, every excavation a few feet in depth penetrates the stratified material. This relationship is frequently seen in the deeper road cuts. Not uncommonly the stratified drift outcrops in small areas on the crests or steep slopes of a hill, while the greater part of the surface is covered with till, or with a stony clay which has not been distinguished from it. In some cases the topography seems to be determined by the underlying stratified gravel and is no more than slightly modified by the thin veneering of till.

Much of the till is not of the normal type. This abnormal phase is stony but not gritty. On the contrary, it is very clayey. It has a more or less greasy feeling, a waxy or glazing surface when cut, and a pronounced tendency to crack on drying. Many of the pebbles are coated with a thin film of clay, which is not easily removed. The color is dark red, tinged with brown. This clayey till occurs most

*Annual Report of the State Geologist of New Jersey for 1892, pages 56, 57, 142.

commonly at low levels of the lake basin, 180 to 210 or 220 feet, but it is by no means limited to these heights, having been observed at a number of places at heights up to 270 feet. It is not possible to say to what extent this till was formed beneath the ice and afterwards submerged, and to what extent it was formed beneath water by the combined action of icebergs and water. Normal, gritty, stony, foliated till is not uncommon within the lake basin, and sometimes occurs in close proximity to the clayey, waxy till. This might suggest that the latter is due to iceberg action rather than to the modification of glacial till by submergence. On the other hand, the peculiar type of stony clay here referred to seems to be much too continuous over considerable areas, and too closely confined to the lower level, to make its reference to bergs plausible. Nowhere has this clayey till been found upon the sides of the basin up to the shore line. The author is informed by Professor Salisbury that something similar to it has been found on the low-lying (forty to fifty feet) Triassic areas outside the lake basin near the coast, where post-glacial submergence may have occurred.

THE OUTLETS OF LAKE PASSAIC.

Liberty Corner outlet.—A mile and a half west by north of Liberty Corner, at Moggy Hollow, is a notch in the rim of the basin, through which Lake Passaic drained during its maximum stages. The bottom of the notch has an altitude of 331 feet, and with the exception of the gaps at Little Falls and Paterson, and the low ground along the Pompton river, all of which were closed by the ice when the lake existed, this is the lowest point in the rim of the basin. That a large stream of water formerly flowed through this notch is at once evident (1) from the size and shape of the notch itself, and of the valley below the notch, (2) from the deposits in the North Branch of the Raritan at and below its junction with the lake outlet, and (3) from the deposits in the lake basin at the entrance to the outlet.

The notch is a flat-bottomed, steep-sided trench, sixty yards wide at the bottom and 157 yards wide at the height of the maximum lake level. Figure 9 is a sketch made from a photograph, looking down the outlet.

The notch is cut in hard trap rock, which outcrops at many points on the sides and bottom. Just east of the entrance to the notch is a broad, ill-defined divide, at an altitude of about 331 feet, between a

stream flowing eastward into Passaic river and another flowing westward into the North Branch of the Raritan. Westward from the divide the bottom of the notch falls sixteen feet in the first 1,100 feet, and then makes an abrupt fall of twenty-five feet. Below the fall the bottom of the gorge is marshy for some distance. The stream which at the present time flows from the 331-foot divide through the notch and over the fall is so insignificant that it is impossible to suppose the notch, as we find it to-day, to have been cut by it. It is also impossible to suppose that the bottom of the notch has been lowered an appreciable amount by it since lacustrine times. It is equally inconceivable that the notch, in its present form, could be the col be-

Fig. 9.

Moggy Hollow outlet, looking down the valley, which turns abruptly to the left in the background. (Drawn from a photograph.)

tween the headwaters of two pre-glacial streams. Its form is altogether conclusive that it was the channel through which flowed a stream of water whose average width was about 150 yards, and whose depth was sufficient to give it great velocity. In pre-lacustrine times there may have been a col on the site of the notch, but the notch in its present form is due to erosion by the outflowing current.

About a quarter of a mile below the falls, the gorge loses, to some extent, its flat-bottomed character, and the present stream has slightly eroded the bottom. Where the valley passes from the trap to the underlying sandstone and shale, three-quarters of a mile west of the

first falls, another waterfall has developed. A short distance below the second fall the valley widens out into the broad flat which borders the North Branch of the Raritan. On this flat are strewn many trap cobbles and bowlderets up to one foot in diameter. These pieces of trap were quarried out of the notch, or out of the valley immediately below it, and were carried down to their present position by the outflow of the lake. They are far too large to be handled by the present stream, which, indeed, it has been necessary to ditch in order to get it across the deposits made by the outflow of the lake.

Below the junction of this valley with the North Branch, the flood-plain of the latter is a little wider than above the junction, and its materials are more than ninety per cent. of trap, many of the fragments being beyond the power of the present stream to carry. Above the junction, trap pebbles do not form more than ten or fifteen per cent. of the deposits of the valley plain. These deposits confirm the conclusions already drawn from the form and size of the outlet, that a stream of considerable dimensions and of great velocity flowed through the notch in comparatively recent times.

A significant feature in this connection is the number of large, fresh gneiss bowlders, similar to those found in the moraine, which occur below the shore line near the entrance to the outlet. They are more abundant here than at other points in this part of the lake basin, and are taken to indicate that currents set towards the outlet, bringing to this point bowlder-bearing icebergs.

In juxtaposition to the outlet there is a considerable body of drift, some of which is glacial. It extends to a maximum height of 435 feet in this vicinity, and downward below the level of the lake. One phase of the drift is exposed in a pit a quarter of a mile south of the outlet. Here the drift is seen to be compact and stony, with a matrix composed largely of gneissic material. The stones are generally small, under eight inches, and consist of various quartzites, similar to those of the Triassic conglomerate, decomposed gneiss, Potsdam (?) sandstone, Hudson river (?) shale and slate, Triassic shale, flint and trap. A more satisfactory exposure of the drift occurs along the road toward Liberty Corner, where the till character of the drift is shown. At first thought, the presence of this body of drift about the outlet at heights seventy-five feet above any possible lake-level, might seem fatal to the lake hypothesis. But this drift has nothing to do with the lake. It is to be correlated with the bodies of extra-morainic

drift found in other parts of the State, which are confidently believed to be much older than the morainic, and to have no chronological or genetic connection with Lake Passaic. That part of this drift, however, which is below the lake level was doubtless more or less modified by lacustrine agencies, and may be, in part, berg drift.

The Millington gorge.—The Passaic river escapes from the area of the Great swamp by a deep, narrow gorge through Long Hill, at Millington. The gorge is sixty to seventy feet deep, very steep-sided, and, so far as its shape is concerned, seems to be of very recent origin. If the gorge were to be filled up for sixty or seventy feet from its base, so that the top was 280 or 290 feet in height, a basin would be formed in the area of the Great swamp, the lowest point on whose rim would still be at this gorge. If this gorge has been eroded since the maximum lake stage, and some things may be said in support of this proposition, we must conclude that after the ice had freed the Little Falls-Paterson outlet, and thereby drained a large part of the lake, and brought the level of the remainder below the Moggy Hollow outlet, a small lake still occupied the area of the Great swamp, and that it persisted, with constantly-diminishing level and area, until its outlet across the trap ridge at Millington had been cut down nearly to its present level. Judging from the shape of the gorge, the maximum amount of post-lacustrine cutting might have been sixty or seventy feet, the bottom of the outlet being originally, in terms of the history of Lake Passaic, at an altitude of 280 or 290 feet. It certainly could not have been more than eighty-two feet above the present channel, for at Lyons station there is a sag in the rim of the basin at an altitude of 303 feet, that is, but eighty-two feet above the river at its entrance to the Millington gorge. If the gorge at Millington were filled up to a level higher than 303 feet, the hypothetical remnant of Lake Passaic would have been drained by way of Lyons station and Harrison's brook instead of via Millington. If the gorge at Millington was cut in post-lacustrine times, the Great swamp lake must have existed for a considerable period after the rest of the lake basin had been drained, for the gorge is cut in trap rock, and the stream flowing from the Great swamp lake must have been free from sediment, and so have had but slight cutting power.

If the Millington gorge be post-glacial, shore marks at heights corresponding to its top, and to levels below its top, might be expected to exist. A few beds of shore gravel have been found at heights vary-

ing from 285 to 295 feet. Two well-marked beds of red shale gravel (c 17, 285 feet; c 18, 291 feet) occur along the road between Basking Ridge and Madisonville, and traces of water-worn trap pebbles were found along the road three-quarters of a mile west of Green Village. But shore features at this level are neither so numerous nor so distinct as we should expect in a lake lasting the length of time necessary to cut the gorge in the hard trap. It should be remembered, however, that the lake was much reduced in size at this stage, and that it waves were correspondingly less efficient.

If the gorge be the result of post-lacustrine erosion, there should be considerable deposits of trap gravel along the Passaic just below the gorge. The material could not have been carried away, since beyond the gorge the stream is far too sluggish to carry gravel. Trap gravel is present in the bed of the stream and in the flood-plain, but apparently not in great quantity. From lack of exposure its quantity may be underestimated.

Again, if the gorge be post-glacial there should be lacustrine deposits in the Great swamp area belongiug to this later period. But, as has already been shown, the clays of the Great swamp area underlie sand and silt deposits, which antedate slightly the formation of the moraine. With the exception of the humus accumulations in the lower parts of the swamp, deposits later than these sands and silts are not present in the area which would have been occupied by the supposed lake. It is difficult to believe that the hypothetical lake could have existed, as supposed, and not formed deposits above the glacial sand and silt. In spite, therefore, of its youthful appearance, the weight of evidence seems to be strongly against the post-lacustrine erosion of this gorge. An additional reason for this conclusion is found in the comparison of the Millington gorge with the post-lacustrine gorge at Stanley. This evidence is given a few paragraphs below.

Several suggestions may be made concerning the date of erosion of this gorge, but the data at hand do not warrant any positive assertions. In connection with the discussion of the history of Lake Passaic, the possibility of a lake having existed in the Great swamp area in inter-glacial time is considered. The outlet of this lake may have been across Long Hill at Millington, and the present gorge may have been partly eroded in inter-glacial time. As will be seen later, there is good reason for postulating the existence of this inter-glacial lake.

In the light of what is now known, this origin of the gorge is at least a plausible one.

The Stanley outlet.—Near Stanley, the valley of the Passaic is much constricted and the river in post-lacustrine times cut a passage across a dam of drift. The amount of post-glacial cutting is here about twenty-five to thirty feet. Eighteen feet of it is in drift, the remainder in red shale. The passage which the river has cut here is much wider, less steep-sided and less deep than the gorge at Millington. The differences in width and slope are due to the difference in hardness of the materials through which the stream has cut. The difference in depth between the post-glacial cut at Stanley and the gorge at Millington is most significant. All conditions seem to favor erosion at Stanley as compared with Millington—1°, the size of the stream is greater at Stanley; 2°, the gradient just below Stanley is much greater than below Millington; 3°, the material in which the stream has had to cut is very much more easily eroded. If under these favoring circumstances the post-glacial cutting at Stanley has been no more than the figure cited above, the amount of the post-lacustrine erosion at Millington must have been much less.

The altitude of the obstruction at Stanley through which the river has cut was about 230 feet. It would seem that after the ice freed the Little Falls-Paterson outlet, a long, narrow lake must have existed, temporarily, behind this barrier in the valley between Second mountain and Long Hill. If the Millington gorge were as low as at present, the Great swamp must have been a greater swamp, hardly a lake, at this time. The lake between Second mountain and Long Hill must have been shallow, its greatest depth not much exceeding twenty feet. The lake must have been studded with islands. It must have been short-lived, since the upper part of the barrier at Stanley, down to about 212 feet, was composed of easily-eroded till. When the outlet was cut to this level, the lake would have mainly disappeared. A single bed of shale gravel, six feet thick, was found a mile southwest of Gillette station, at a height which permits its reference to this lake It is interesting to note further that all the lacustrine clay between Long Hill and Second mountain lies below the level of such a lake as is here described, and furthermore, that most of the surface below this level is clay-covered. So small a body of water could not have had waves of much strength, and its deposits must have been, for the most part, of a clayey nature. The lacustrine clay seems to indicate

very clearly that such a lake existed.* It must have been ten to twelve miles in length, and a mile to a mile and a half in width. It was confined to the low area immediately adjacent to the Dead and Passaic rivers. Since the latter name has already been appropriated, this subordinate lake may be called Dead lake, an appellation which has a double fitness.

Little Falls gorge.—Second mountain is broken by a gap more than two miles wide, where it is crossed by the Passaic river at Little Falls. The bottom of this gap is nearly flat and is covered with a thin coating of till, clay and fine sand. At Little Falls the Passaic river has cut through this drift covering, which here does not exceed ten feet, and has eroded a channel in the trap beneath. On the glaciated ledges of trap on both sides of the river are many pot-holes of varying sizes. Most of them are shallow, and appear to have been more or less worn away by glaciation. The height of these pot-holes is 179 feet, and their presence on a glaciated surface seems to indicate that in pre-glacial times the river had here cut the trap down to this level. Above the trap, as indicated, the drift is not more than ten feet thick. It is, therefore, safe to conclude that when Lake Passaic was drained, after the retreat of the ice, the waters could not have been held here at a height of more than 190 feet, and must have been held to a height not more than 15 feet less than 190 feet.

Midway between Little Falls and West Paterson the river, which is flowing northeast, makes a sharp turn to the southeast, and then, half a mile beyond, makes a sharp turn to the left, resuming its northeasterly direction. These turns are caused by two enormous kames, which are built, like a dam, almost across the valley. At its second bend, the river flows around the southeastern end of this dam, in a narrow valley between the drift and the trap of First mountain. At first sight it might appear that the drift once completely dammed the valley at this point, and that the river has since cut its way through it. In this case the waters of the lake must have been held for a short time at about 250 to 255 feet. Careful examination of the valley at this point, however, seems rather to show that the drift never completely filled it, but that the river found a passage around

* It is not meant to affirm, however, that all the entire thickness of the clay between Long Hill and Second mountain necessarily belongs to the late stage of the lake. The lower part of it may belong to the earlier and more extended periods of Lake Passaic.

the end of the kame, being shifted by the drift to the right-hand side of its valley, against the trap of First mountain. The sides of the kames where the river makes its first bend to the southeastward are being eroded by the lateral cutting of the river, whereas the end of the kame around which the river swings at the second bend does not show signs of erosion, but appears to have a constructional slope.

At West Paterson the Passaic river crosses First mountain through a gap two miles wide. In the bottom of this gap the river has cut a deep gorge, at the upper end of which the stream plunges over the side of a narrow cañon seventy feet deep. When the ice had so far melted as to open this outlet, the river must have flowed at an elevation not higher than 150 feet, and not lower than 125 feet, for at higher levels the water would have chosen some other channel. Since this height is at least twelve feet lower than the height of the lowest swamps in the lake basin, this rocky barrier could not have caused subordinate lakes within the Passaic basin.

Great Notch.—Three miles south of Paterson, First mountain is cut by Great Notch, a deep, narrow, steep-sided gap, whose bottom has an elevation of 303 feet. It is conceivable that during the retreat of the ice, the gap in Second mountain at Little Falls was opened, before the gap in First mountain at West Paterson. In this case the lake must have overflowed through the Great Notch at an altitude of 303 feet, if the ice freed the Notch before it did the West Paterson outlet. Since they are so near together, the West Paterson gap would be expected to be opened very soon after the Little Falls gap, and therefore the outflow through Great Notch, if it took place at all, could not have been of long duration. If the water escaped there, even temporarily, it must have stopped the outflow west of Liberty Corner. Moreover, it is possible that Lake Passaic drained through a passage under the ice before its front melted back beyond the Little Falls gap. In this case the Great Notch gap may not have been used. Examination of the notch failed to reveal data which could be regarded as indicating either that the lake did or did not drain through it at any time.

The drift-filled gap at Short Hills.—At Millburn, First mountain is broken by a gap a mile and a half wide. Although drift incumbered, the lowest point in this gap has an elevation of 100 feet A. T. Opposite and west of this gap the moraine crosses Second mountain, between Short Hills and Summit. West of Short Hills the surface

rises slightly above 380 feet. This elevation represents the lowest point of the gap in Second mountain, almost two miles west of the gap in First mountain at Millburn. From the bottom of this gap, at 380 feet, the surface descends westward towards the lake basin, and eastward towards the wide gap in First mountain. The average height of the trap crest of Second mountain northeast of this gap near Short Hills is 575 feet. Its average height towards the southwest is 550 feet. Since the morainal accumulations in the vicinity of Short Hills are great, it is evident that the gap in Second mountain, opposite the gap in First mountain, is very much more considerable than it seems. Some idea of its size may be obtained when it is recalled that, even with the drift-filling, the surface is 170 to 200 feet lower than the average height of the crest of Second mountain.

A few years ago a deep well was dug about a mile north of the Short Hills depot, and nearly in the middle of the 380-foot sag. The elevation of the surface at the site of the well was about 370 feet A. T. The well was sunk *200 feet* without reaching the trap rock.* The rock bottom of this gap, therefore, must be below 170 feet A. T. That it must be considerably less than 170 feet is shown by the following data—1°. At the greenhouses of Mr. Jones, opposite the Short Hills depot, a well was sunk 150 feet without reaching rock. The elevation of the surface at the site of this well is about 200 feet. Rock at this point is therefore less than fifty feet above sea-level. The well is located in the shale valley between First and Second mountains, and in line with the gaps in First and Second mountains, respectively. 2°. A quarter of a mile east of this boring is the well which supplies Short Hills with water. This well has an elevation of 200 feet A. T. and is 200 feet deep, at which depth rock was struck. Therefore the rock bottom of the gap in the shale between First and Second mountains is at one point known to be at sea-level, and this is not known to be the lowest point. The known deep gap in Second mountain near Short Hills, the deep gap in First mountain at Millburn, and the known deep buried valley between the two mountains, and in line with the two gaps, give strong suggestion that a pre-glacial stream flowed through these gaps to the sea. Apart from this gap in Second mountain near Short Hills, the lowest possible preglacial outlet of the basin was at Little Falls, and this could not

* These data and those concerning the third well mentioned below were obtained from Mr. Stewart Hartshorn, Short Hills, N. J.

have been lower than 180 feet. The boring referred to, therefore, reached a level ten feet lower than any other possible pre-glacial outlet of the Passaic basin. This is sufficient to demonstrate the suggestion just made that a stream must have flowed through the gaps in First and Second mountains, at Short Hills and Millburn, respectively, and thence to the sea.

This leads to another important inference. It will be remembered that the bottom of the rock valley between First and Second mountains is known to be as low as sea-level at one point, and that this is not known to be its lowest point. Now, if the rock bottom at the gap in Second mountain be no lower than 170 feet—the bottom of the boring—the pre-glacial stream must have had a fall of 170 feet on the south face of Second mountain. The width of the gap is such as to militate against this conclusion. It is so great as to indicate that the stream which occupied it was of considerable age. The chances against it being possessed of any such fall are good. It is probable, therefore, that the rock gap in Second mountain is very much lower than 170 feet, the height at which the boring ceased.

It follows that the main drainage of the Upper Passaic basin in pre-glacial times must have been through the Short Hills-Millburn gaps. Manifestly, therefore, Lake Passaic could not have come into existence until the first of these gaps was closed.

The Summit Notch.—A little east of Summit station is a narrow, steep-sided notch in Second mountain. Its bottom is now at an elevation of about 320 feet. About Summit station and westward there are thick accumulations of drift. The elevation of Summit station is 387 feet. It would seem that the narrow notch east of the station must have afforded an outlet for the lake at a level of 320 feet before the drift to the west and westward was accumulated. No evidence of such overflow could be discoverd. But since the ice afterwards covered this notch, such evidence could not be expected to exist. The possible existence of this outlet introduces another factor into the problem of the pre-morainic history of the lake, and renders the problem still more complicated. But the insignificance of this notch, in comparison with the gap at Short Hills, is such as to make it probable that this notch did not play an important role in the history of the lake. Nevertheless, the possibility that for a time at least the pre-morainic lake, if it existed at all, may have overflowed at this notch must be kept in mind.

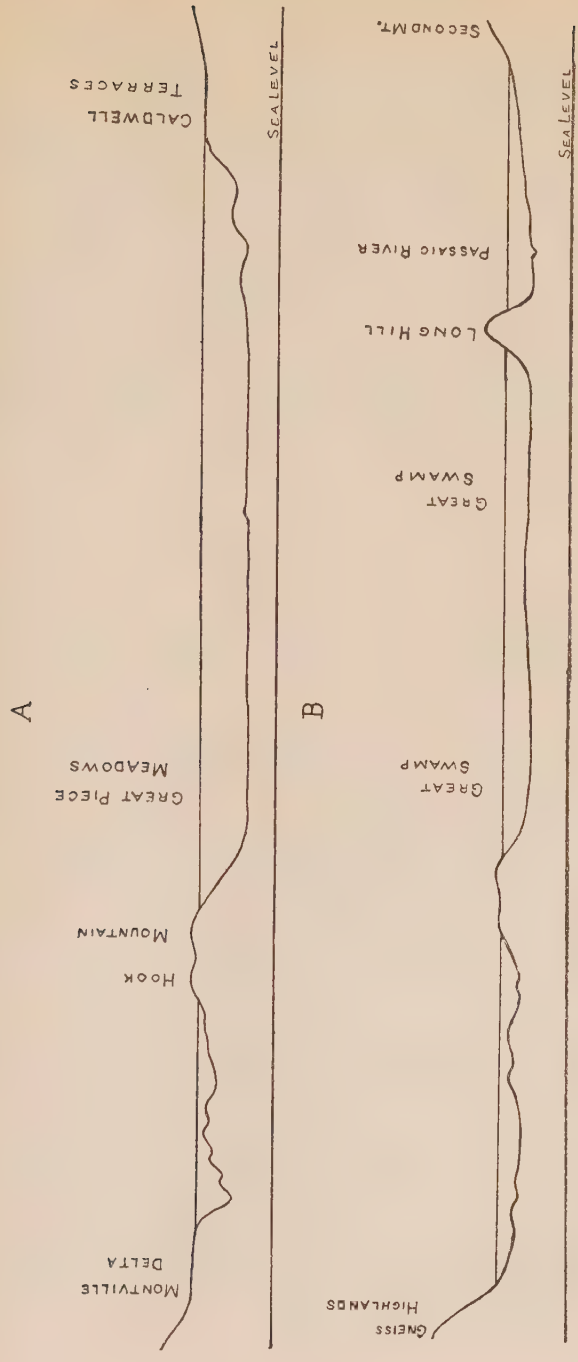

Fig. 10.

Sections of Lake Passaic Basin. A. From the Montville delta to Caldwell. B. Along a line a little northeast of New Vernon and Berkeley Heights. Horizontal scale, 1 mile to one inch. Vertical scale, one-eighth inch to 100 feet. Vertical scale about six and a half times the horizontal scale.

THE HISTORY OF LAKE PASSAIC.

Study of the heights of the various gaps in the rim of the lake basin reveals something of the pre-glacial drainage of that region. Through the lowest gaps, those at Short Hills and Millburn, the larger part of the present Passaic drainage escaped. Another stream of much less size, draining the northeastern part of the Passaic basin west of Little Falls, probably flowed through the gaps at Little Falls and Paterson. The drainage areas of these two streams could have been separated by no more than a low divide, as shown by the present topography. Apart from the gaps occupied by these two streams, there were no deep depressions in the rim of the basin. The next deepest was Great Notch, the bottom of which is now 303 feet A. T.

THE ADVANCE OF THE ICE.

For a time after the ice sheet reached the gaps in the trap ridges at Little Falls and Paterson, the river which formerly flowed through these gaps may have been able to keep its channel open beneath the ice. So long as this was true, no lake could have been formed within the Passaic basin. But there came a time when such a sub-glacial outlet, if it existed at all, was closed. When this occurred the drainage which, but for the ice-blocking, would have escaped to the sea via Little Falls, must have accumulated in front of the ice in the northern drainage basin referred to above. Any lake which may have been formed at this time must have been small and shallow, for it must soon have overflowed the low divide, separating the drainage basin which had its outlet at Little Falls, from that which had its outlet through the Short Hills gap. This divide was in all probability lower than 303 feet, the height of Great Notch, which, therefore, could not have served as an outlet at this time. As the ice advanced it encroached upon this hypothetical early lake, displacing its water and diminishing its size. This process continued until the ice had displaced all the water, and so destroyed the lake. No lake could have been formed in the drainage area of the river which flowed through the Short Hills gap, until after the ice reached that gap and filled it. Then, and not until then,

could a lake have existed in the basin south of Morristown. For a time the waters of this lake may have escaped through the narrow notch at Summit (height 320 feet), but since this notch is so close to the Short Hills gap, it must have been filled by the ice very soon after the Short Hills gap was occupied. The lake then drained through Moggy Hollow near Liberty Corner, where there is now a notch, the bottom of which is 331 feet above tide. It is not necessary to assume that when the lake first overflowed at this point the outlet was at this elevation. On the contrary, it was somewhat higher. During the period when this notch served as the outlet, erosion cut it down to the present level. From the evidence of shore lines in the immediate vicinity of the outlet, it is certain that the amount of erosion here cannot have been greater than twenty-five feet. It may have been a little less.

The sequence of events outlined above is based upon the assumption that all the drift in the Short Hills gap is late glacial, and that until the ice reached the line of the moraine, drainage escaped through this gap at the level of the rock bottom. On this assumption, no lake except a shallow one in the northern part of the present basin could have existed until the ice reached the line of the moraine and filled this gap. But certain facts have been observed, which suggest the existence of a pre-morainic lake in the southern part of the basin. In the region of the Great swamp extensive deposits of clay are known to exist. By their relationship to overlying deposits these are clearly shown to antedate the moraine and accompanying overwash plain. If this view be correct, and there seems no escape from it, a lake must have existed in the Great swamp area for a considerable period before the ice reached its maximum extension.

Three hypotheses concerning such an early lake may be considered—

1°. Some part, perhaps a large part, of the drift-filling of the Short Hills gap may belong to the earlier ice invasion which deposited much of the extra-morainic drift found more or less abundantly about the lake basin. In this case Lake Passaic might have come into existence for the first time, when the ice filled the Little Falls gap. It would have overflowed through the drift-clogged Short Hills gap while the ice was advancing from Little Falls to Short Hills, if this gap were lower than Moggy Hollow (356 feet). Under this hypothesis, the Great swamp clays could then be referred to this part of the lake's history. Under this hypothesis, it must be assumed

that the ice advanced very slowly, so slowly that more than 100 feet* of clay accumulated before the deposition of the overlying loam, sand and gravel, which is correlated with the greatest advance of the ice. The very general occurrence of these clays at levels below 240 feet might be taken to indicate that the Short Hills gap had this elevation. The clays north of the moraine, which are similar to lacustrine clays, are also in general at low levels, and so far as elevation goes, may have been formed in a lake draining as thus suggested. This hypothesis makes all the clay of the Great swamp, which may be lacustrine, later in origin than the closing of the Little Falls gap by the last ice advance.

2°. It may be conceived that the earlier ice invasion wrought such changes in the pre-glacial topography that, after its retreat, a low-level lake occupied the area of the Great swamp, and perhaps also of the lowlands north of the moraine. In this lake much of the lacustrine clay may have been formed. It may be supposed further that the lake was drained during inter-glacial time by the clearing out of the Short Hills gap. In this case the clays ought to be overlain by an old soil. Above this old soil would come whatever deposits were made in the lake of the later glacial invasion. So far as known, such an old soil does not exist. The upper part of the clay, including all that exposed in the various clay pits, and in one or two newly-dug wells, to a depth of twenty feet, grades into the sand and silt or stony clay which overlie it. In comparison, however, with the whole area, the points at which observations have been made are few and the exposed sections shallow, and it is not certain that such a soil does not exist.

3°. The third hypothesis differs from the second only in the assumption that the inter-glacial lake lasted until the later ice invasion, and was continuous in time with the lake formed in consequence of that invasion. According to this hypothesis the clays may be all or nearly all early-glacial and inter-glacial. They would pass directly into the deposits of the later lake without the intervention of an old soil. In so far as there is no knowledge of such a buried soil this hypothesis is favored.

The first hypothesis makes the clays, so far as they are lacustrine, entirely late-glacial. The great objection to it is the very long time

*Annual Report of the State Geologist of New Jersey for 1892, page 139. It is not certain that the great depth of clay and alluvium here cited is all lacustrine.

required for the advance of the ice in order to permit the formation of so great a body of clay, compared to the time of its maximum extension and retreat. The silts and sands correlated in time of origin with the moraine are not buried by any later deposits.

The second hypothesis makes most of the clays early-glacial and inter-glacial, and seems to demand an old soil separating these deposits from the later ones. Such a soil is not known to exist, neither is it known positively that it does not exist. The third hypothesis makes most of the clays early-glacial and inter-glacial, and it demands their transition upward into the later deposits without a break. Against this hypothesis there do not appear to be fatal objections. But if the amount of inter-glacial erosion was as great as it has sometimes been thought to be, it would hardly be expected that such a lake could have endured through all the interval between the first and last ice invasions.

The clays about Mountain View and Little Falls, so far as they may be lacustrine, may be accounted for on either of the three hypotheses—on the third more readily than on either of the others. The presence of stratified drift directly beneath a more or less thin coating of till, over a large part of the area from Madison and Chatham north to Hanover Neck and Whippany, may find explanation on either of the three hypotheses, although it is difficult of explanation on the assumption that a lake never existed in the upper Passaic valley until the moraine filled the Short Hills gap.

Although there is much indefiniteness concerning the pre-morainic history of the lake, facts seem to indicate that there was such a history. No such indefiniteness prevails concerning the post-morainic history. It is not implied that all the stages of the later history can be made out, but they are certainly clearer than the earlier stages.

The Madison stage.—When the ice had reached the limit of its maximum advance, the area of the lake was at a minimum, and at this time it must have overflowed through the Moggy Hollow outlet near Liberty Corner. The lake seems to have remained at approximately the same level during the time when the moraine and the subaqueous overwash plain were formed. During this period of maximum level there were formed, in part at least, the high-level shore lines in the extra-morainic basin. Correlated with these is the broad subaqueous overwash plain extending from Chatham to Morristown, and perhaps also the somewhat lower plains near West

Summit. The pebble-strewn terrace in Mr. Apgar's orchard at Moggy Hollow (A 4), the gravel deposits near Bernardsville (a 12, b 1), Basking Ridge (c 16), Lyons (c 15, c 12), Millington (c 11, c 10), Union Village (a 2, a 1), New Providence (c 3, c 4), New Vernon (d 1, d 2, d 3), and one and a half miles south of Morristown (d 5, d 6, d 7), together with the subaqueous overwash plain, are all referred to this stage of the lake. This may be called the Madison stage, from the fine development of the subaqueous overwash plain west of that place. It is hardly to be expected that the lake remained at absolutely the same level during this stage. There were undoubtedly minor oscillations of a few feet from time to time, due to varying rates of melting of the ice. Whatever may have been the ratio of drainage from the surrounding hills to that from the ice in the early history of the lake, during *this* stage, owing to the diminution of the land-drainage area, the melting ice must have supplied by far the greater part. Such oscillations of level would be best shown upon such shore features as were of rapid growth, as for example the subaqueous overwash plain. In this way perhaps many of the minor inequalities in the height of different lobes are to be explained. It will be remembered that the various shore features, described in detail in preceding pages, and correlated with the Madison stage of the lake, are not now at a constant elevation. These differences are too great to be ascribed to any minor oscillations. They are to be explained on the hypothesis of post-lacustrine warping of the earth's crust, a subject which will be more fully discussed a little later.

THE RETREAT OF THE ICE.

As the ice melted back from the moraine, the lake increased in area by successively filling that part of the basin from which the glacier withdrew. During this period the lake must have been more or less completely divided into two parts by the moraine, which, for part of its course across the basin, rises above the maximum water-level. This barrier did much to prevent debris-bearing icebergs from reaching the extra morainic basin, and thus limited the time in which such deposits could be made, to the period of ice advance.

A study of existing glaciers, which have both a water front and a land front, has shown that when they remain in a condition of equilibrium or of retreat, the water front melts back more rapidly than

the land front and an embayment is formed. This is shown in several of the Greenland glaciers and in the Muir glacier of Alaska.* That this was more or less true of the continental ice sheet, where it was margined by glacial lakes, is shown by the study of many of these lakes. The deltas of Lake Agassiz, together with the terminal moraines of that region, show that "against this great lake the ice was melted back faster than on the adjoining land areas."† Mr. Upham states that the "extent of the indentation of the ice boundary was fifty to one hundred miles back from the lobed extensions of the ice sheet on each side."‡ To a less extent the same thing was true of the water front of the glacier where it crossed the glacial ancestor of Lake Champlain.§

The same thing seems to have occurred in Lake Passaic during the retreat of the ice. An embayment of several miles back from the ends of the land lobes marked the front of the glacier where it crossed the basin of the lake. The glacial deltas between Boonton and Parsipanny, southeast of Boonton, north of Montville, at Jacksonville, Upper Preakness and Caldwell, were all formed by glacial streams, while the ice edge was in the immediate neighborhood. The ice seems to have remained upon the higher ground above and back of these plains, after it had retreated from the lower ground in the same latitude. This is shown (1°) by the basinward slope of the surfaces of the plains, showing that they were built *from* the highland; (2°) by the forward-plunging strata, which, where seen, generally dip toward the lake and away from the highlands; (3°) by the frequent occurrence of bowlder-strewn kames at the heads of the plains, which, it is believed, marked the position of the ice while the plain was being formed; and (4°) sometimes by the forms of the margins of the deltas next the highlands above the lake.

The other possibility, that these plains were formed in depressions between the highland on one side and the edge of the ice, which filled the lower ground of the lake basin on the other and supplied the material, was kept in mind as a working hypothesis in the field, but was finally abandoned, since it does not match the facts. In terrace plains formed in this way, the surface should slope towards the

*S. Prentiss Baldwin, Amer. Geol., Vol. XI., page 374, *et seq.*

†Warren Upham. Glacial lakes in Canada. Bulletin of the Geological Society of America, Vol. II., page 273, *et seq.*

‡Baldwin, *loc. cit.*, where Mr. Upham is quoted.

§Baldwin, *loc. cit.*

highland, not away from it; the beds should dip in the same direction, and the edge of the plain should, by the character of its slopes, indicate that the material had slumped down as the ice melted; or, in other cases, should preserve the knob-and-hollow type of irregularity which represents, in reverse, the irregularities of the surface of the ice, against which the sand and gravel of the plain were deposited. These criteria are wanting, except next the highland margins of the deltas, where they are explicable on the other hypothesis.

The Upper Preakness stage.—At a number of places, more or less well-defined terraces are present at elevations varying from sixty-five to seventy-five feet lower than the maximum water-level. These lower terraces are sometimes directly in front of the higher, which rise from the upper margin of the lower. In other localities, the higher are present without the lower, or the lower without the higher. The two are seen in close connection between Boonton and Montville, at Upper Preakness and west of Haledon.

The time relationship of these terraces to those of greater altitudes is of great importance in interpreting the history of the lake. It is assumed that the tops of these terraces represent the actual level of the water in which they were formed, just as it has been assumed that the surface of the subaqueous overwash plain marks the maximum water-level. At Upper Preakness the lower terrace takes the form of a perfect glacial delta, having an area of nearly a square mile. If the generally-accepted theories as to the formation of deltas are correct, there is no escape from the conclusion that the top of this delta marks within a few feet the level of the water at the time of its formation. These terraces, therefore, mark a subordinate stage in the lake's history, which may be called the Upper Preakness stage, from the marked development of the delta plain near Upper Preakness. The time relationship of the upper to the lower terrace seems to be clearly shown at Upper Preakness, less distinctly south of Montville and west of Haledon. At Upper Preakness, the lower glacial delta plain at 335 to 340 feet was undoubtedly formed while the ice edge stood at the kame moraine belt, which borders the plain on the north. This kame belt rises forty to eighty feet above the level of the northern edge of the plain. At a later period, after the ice had melted back a mile or more, the upper plain, in so far as it was developed beneath the water, was formed in water standing at about

412 feet. According to the terms of this hypothesis, the lower flat clearly antedates the upper. It should be said, however, that the plain north of the kame or moraine belt, which lies just north of the Upper Preakness plain, is, in places, markedly undulatory. It is not believed that it is strictly a delta plain, though there seems to be evidence that its surface was, in some places, modified by the water of the lake.

South of Montville, the lower terrace is 150 yards wide, nearly a quarter of a mile long, and falls off steeply in a lobate front for forty or fifty feet. Save at one point, it is separated by depressions from the front of the higher terrace. At this one point, the flat rises to a bowlder-strewn kame, which is partially buried by a projecting lobe of the upper terrace. The relationship here is such as to render improbable the hypothesis that the lower flat has been cut by the waves from the upper terrace, or that the upper has supplied the material for the formation of the lower. No stream channels dissect the surface of the upper flat, as would be the case had the lower been formed after the upper, and of material supplied by streams which crossed the surface of the higher plain and emptied into water standing at 320 to 330 feet. The conclusion here is the same as that drawn from the Upper Preakness plains, that the lower terraces are older than the higher. Near Boonton the lower terrace is quite well marked along the front of the upper slope, but there the relative age is not clearly indicated. Although the data at that point do not show the younger age of the upper flat, they show nothing to the contrary. West of Haledon, the relationship of the terraces favors the hypothesis that the lower terrace is the older, but the evidence is not so strong as at Upper Preakness. Nowhere is the relationship between the two such as to necessitate the assumption of the greater age of the upper terrace.

On the assumption, therefore, that these delta plains mark the water-level at the time of their formation, it would seem that the front of the ice became deeply embayed as it retreated from the line of the moraine, and that the waters of the lake sank about seventy feet below the Madison level. During this lower stage, the 320–325-foot terraces from Boonton to Montville, the ill-defined flat between the first and second canal planes at Montville, possibly the terraces (340 ± feet) north of Jacksonville, the 335–340-foot plain at Upper Preakness, and the lower terraces (340 feet) west of Haledon were

formed. Perhaps the red shale gravel beds between Madisonville and Basking Ridge, which are about eighty feet below the maximum shore lines, belong to this stage, though this is not at all certain. No other shore features were observed in the extra-morainic basin, which by any possibility can be referred to this stage of the lake. The Upper Preakness stage, if it existed at all, was probably a short one, since the terraces are not of great size, and deposits of this character were undoubtedly built very rapidly. In order to account for the lowering of the lake-level from the Madison stage to the Upper Preakness stage, it is necessary to assume that the lake had, at this time, a sub-glacial outlet. There could have been no surface outlet, as the present topography shows, and climatic changes, or possible changes in the rate of ice-melting, do not at all meet the case. There appears to be no difficulty in the way of supposing that a sub-glacial outlet might be brought into existence, as the ice retreated toward the Little Falls gap. But the difficulties involved in the assumption of such a sub-glacial outlet, as is necessary to account for the existing phenomena, are considerable. They will be considered after the next succeeding stage of the lake has been described.

The Montville stage.—If the above interpretation of the time relationships of the higher and lower terraces is the correct one, the conclusion follows that the low stage of the lake was followed by a rise of water approximately to the Madison level. The name Montville is proposed for this stage of the lake. During it there were formed the high-level plain north of Littleton (f 3) and the delta plains and terraces at corresponding levels north of Parsippany (g 1), between Boonton and Montville (g 2), north of Montville (g 3), at Jacksonville (g 5), north of Upper Preakness (h 2), west of Haledon (h 3) and at Caldwell (h 4). Some of these, especially those on the western side of the intra-morainic part of the lake, may have been partly fashioned during the earlier Madison stage. The ice retreated a little between the Upper Preakness stage and the Montville stage, and the plains of the latter were built a little back of and above those of the former. In some cases the higher plains reached and partially buried the lower ones, and the absence of the lower shore lines in some cases may be due to their complete concealment beneath the later-formed higher plains. Although of essentially the same height as the Madison stage, the Montville stage cannot be associated with

it in time, as shown by the different positions of the ice edge at the two stages.

With the glacial delta plains of the Montville stage are correlated the higher wave-cut terraces on the inner face of the moraine between Madison and Monroe (F 3), the cut terrace and associated spits on the hill between Morristown and Littleton (F 5, f 1, f 2), the gravel bed at the north end of Riker Hill near Livingstone (k 1), the gravel bed on Hook mountain (k 2), and a few other features of doubtful shore origin. The Montville stage seems to have been a little longer than the Upper Preakness stage, but the wave-cut terrace may have been partly formed during the Madison stage before the water sank to the Upper Preakness level. The higher shore features, also, of the extra-morainic basin, particularly the local gravel deposits, may in part belong to the Montville stage, which is believed to correspond in height very closely with the Madison level.

In a few places possible shore lines have been noted at elevations between those of the Montville stage and those of the Upper Preakness stage. They range from fourteen to twenty-five or twenty-eight feet below the highest levels. It has not been possible to correlate them definitely with each other, or to make out their time relationship to the other shore lines. So far as known, they may either precede or succeed the Montville stage. They are best shown on the inner face of the moraine south of Montville, near Caldwell, and northeast of New Vernon.

A cause for the rise of water from the Upper Preakness level to the Montville level must be sought. Climatic changes, and changes in the rate of melting of the ice, may be dismissed as not meeting the requirements of the case. It would seem as though the only cause by which this rise could have been brought about, was the closing of the sub-glacial outlet, by which the lake was previously lowered. It can be readily seen how a sub-glacial outlet might be opened, during the retreat of the ice after it had nearly reached the margin of the lake basin. The lowering of the lake presents no difficulties. But it is not so easy to see how such an under-ice drain, once established, could be closed during the further retreat of the ice. When the ice was retreating, its motion was probably diminishing in vigor, its rate of melting was perhaps increasing, and it was growing thinner. All these conditions would, in so far as they prevailed, oppose the closing of a sub-glacial drain.

There is good reason to believe, however, that the ice did not retreat regularly and always with an equal rate, but that its withdrawal was marked by short periods of recuperation and advance. It is not impossible that an underdrain opened during a period of retreat, might be closed again during one of these slight forward oscillations. The position of the shore features referred respectively to the Upper Preakness stage and the Montville stage, indicates that a re-advance of the ice, if it occurred, did not carry the ice front to the line it held during the lower stage of the lake. Although the closing of the outlet seems a matter of very great difficulty under the most favorable conditions conceivable, yet it is not believed to be beyond the range of possibility.

In summarizing the above discussion, it may be said that the field relationship of the terraces and deltas referred to the two lake-levels, indicates quite strongly that the lower are older than the higher. This fact necessitates the following conclusions: (1°) that the lake secured a sub-ice outlet after the ice had receded as far as Upper Preakness; (2°) that by means of this outlet the lake was lowered from the level of the Madison stage to the level of the Upper Preakness delta plain (about seventy feet); (3°) that the water stood at the level of this and other corresponding delta plains for a time sufficiently long for their construction; (4°) that the sub-glacial outlet was then closed, and that the water again rose to the level of the Moggy Hollow outlet, where it stood during the building of the Montville and other deltas and certain correlated shore features. None of these conclusions, save the fourth, are difficult of acceptance. It is not believed that the closing of the sub-glacial outlet was beyond the range of possibility. Several other hypotheses were considered and the evidence in the field was critically examined with them in mind. All of them presented insuperable difficulties, and they were therefore rejected.

The coincidence in level between the Madison stage and the later Montville stage cannot be used as an argument in favor of their contemporaneity and unity. At first thought the contrary might seem to be true. It might appear that, if the lake sank to a lower level and then rose again, the chances would be vastly against the later high level corresponding with the earlier. But the height to which the lake rose during the Madison stage was determined by the height of the outlet at Moggy Hollow. When the waters rose from the Upper

Preakness level because of the closing of the sub-glacial outlet, their elevation was again determined by the height of the same outlet. The two high-level stages must, therefore, have corresponded very closely in elevation.

The final draining of Lake Passaic.—After the Montville stage had endured for a time, sufficient for the formation of the glacial delta plains which mark that level, but, nevertheless, brief compared to the whole period of the lake, the ice was so far melted back as to permit the escape of the lake drainage through the Little Falls and Paterson gaps. Whether for a short period the water flowed out through the Great Notch is uncertain. If it did, the lake must have been held for a time about ninety feet below the Montville stage. If this stage existed, it must have been very brief, since it has left no positive record. Upon the opening of the Paterson gap the intra-morainic part of the lake was drained to the level of the barrier at Little Falls, about 185 feet. This draining of the lake must have been rapid, since on the many hills within the basin, rising to heights of 200 to 300 feet, there are no shore lines, although many of the elevations are of loose sand and gravel, in which terraces could easily and quickly be cut by shore activities.

Although the intra-morainic basin was drained upon the opening of the Paterson gap, a small post-glacial lake remained in the low ground between Second mountain and Long Hill, in the valley of the Passaic and Dead rivers. It was held at 230 feet by the dam of drift at Stanley, through which the river has since cut a passage. The greatest depth of this lake was not much more than twenty feet. It disappeared gradually as the Stanley outlet was cut down from 230 feet to its present level. If any considerable portion of the Millington gorge in Long Hill is post-glacial, the area of Great swamp also was occupied by a shallow post-glacial lake. If, when the Paterson outlet was opened, the bottom of the Millington gorge was higher than now, by so much as ten feet, the lower part of Great swamp must have been covered by water, and the limits of the swamp considerably extended.

Judging by the meager development of the shore features of Lake Passaic, save in those cases where the supply of material from the glacier was abundant, their indefinite form in many instances, and their entire absence in localities where they might rationally be expected to exist, we cannot but conclude that the entire life of the lake

was, geologically speaking, brief. On the other hand, when we take into consideration the great thickness of lacustrine clay in the Great swamp basin, assuming for the moment that it is all lacustrine, and that it all belongs to Lake Passaic, a very much longer period of time seems necessary.

If, as was suggested on page 64, a lake existed in part of the Passaic basin in the first glacial epoch, and during a part or the whole of inter-glacial time, much of the clay may be lacustrine and yet antedate Lake Passaic.

Summary of the History of the Lake.

Whether a lake existed in any part of the basin in early-glacial or inter-glacial time is not definitely known, but the balance of evidence seems to favor the hypothesis that Lake Passaic had an ancestor. It is, however, certain that when the ice blocked the Little Falls and Paterson gaps, or at latest, when it blocked the buried Short Hills gap, Lake Passaic was born. If not sooner, at least by the time the ice reached its maximum advance, the lake had reached its maximum height, and overflowed its basin at Moggy Hollow west of Liberty Corner. The areal extent of the lake was probably at this time at a minimum. Its length could not have exceeded nine miles, and its greatest width was a little less than eight. This, the Madison level, was approximately constant during the formation of the moraine and the subaqueous overwash plain which fronts it. The greater number of the gravel beds, and the ill-defined terraces of the extra-morainic basin were in part at least formed at this time. The clays of the Great swamp area and vicinity antedate the maximum advance of the ice, since towards the east they pass beneath sand and gravel deposits formed at that time. Too little is known of the Little Falls clays to warrant any positive inference from them concerning the history of the lake. The interpretation of these clays can probably not be satisfactorily made until the whole body of clay in the northeastern part of the State and up the Hudson has been carefully studied. Such study transcends the limits of the work which it has yet been possible to devote to this subject.

As the ice melted back from the moraine, it became deeply indented along its water front, the embayment apparently amounting to something like eight miles. According to the hypothesis presented to account for the lower terraces at Upper Preakness and other places,

the lake sank, during the retreat of the ice, to the level represented by the delta plain at Upper Preakness, a level about seventy feet below a later maximum represented by the Montville delta and the other plains and terraces at corresponding levels. During this stage, which is believed to have been brief, the lake could not have drained through the Moggy Hollow outlet. Its outlet must have been subglacial. After the Upper Preakness stage the waters rose about seventy feet to the Montville level, which is believed to be approximately the same as the Madison level. During the Montville stage were formed the higher terraces found on the shores of the intramorainic basin, and the extra-morainic shore features were probably completed. Fourteen to twenty-eight feet below the Montville deltas there are ill-defined terraces and a few gravel beds at other points, the exact age of which is not determinable.

The final draining of the lake, which occurred after the Montville stage, must have been rapid, since no signs of wave action can be found on the sides of the many hills of loose materials within the basin of the lake. A small post-glacial lake in the Dead river valley, and perhaps another in the Great swamp area, remained until the barriers, which obstructed their outlets at Stanley and perhaps at Millington were cut away, but Lake Passaic may be said to have disappeared on the opening of the gap at Paterson. During its maximum extent, Lake Passaic must have been not far from thirty miles long, ten miles wide at its widest part, and over 225 feet deep in the intra-morainic part. This depth is indicated by the relative height of the Great Piece meadow and the highest shore lines near Boonton and Montville. The greatest depth of the extra-morainic part of the lake could have been little more than 140 feet. The preponderance of evidence seems to indicate very clearly that the life of Lake Passaic was brief.

DEFORMATIONS OF THE LAKE BASIN.

So soon as the heights of the highest shore features of Lake Passaic were accurately determined, it was seen that they were no longer at a constant elevation in reference to the present sea-level. The most important of them are here given in tabular form, the maximum water-level in each locality being taken :

Northwest Side of the Lake Basin.

At Moggy Hollow	A 4.*	356 feet.
Two and a half miles northeast	A 5.	365 "
Basking Ridge	c 16.	367 "
Near Bernardsville	a 12.	369 "
Half a mile northeast of the above	b 1.	371 "
West of New Vernon	d 1.	372 "
One mile east of New Vernon	d 3.	373 "
One and a half miles northwest of New Vernon	b 2.	between 377 and 380 "
One and three-quarters miles southwest of Morristown	d 6, 7.	377 "
One and three-quarters miles south of Morristown	d 5.	between 376 and 380 "
Morristown		probably 376 "
Two miles north of Morristown	f 1.	378 "
South of Littleton	f 2.	382 "
North of Littleton	f 3.	385± "
Glacial delta plain north of Parsippany	g 1.	394 "
South of Boonton	g 2.	394–5 "
South of Montville	g 2.	about 398 "
North of Montville	g 3.	397–8 "
Jacksonville	g 5.	408–9 "

South and East Shore of the Lake.

One mile south of Moggy Hollow	a 10.	349 feet.
One mile southeast of the above	a 9.	347 "
One and a half miles south of Liberty Corner	a 8.	345 "
Mount Bethel	a 6.	350 "
Two and a half miles northeast of Mount Bethel, near Old Home Life Insurance Co. pit	a 3.	358 "
Union Village	a 2.	355–360 "
One mile northeast	a 1.	357–360 "
West Summit deltas		probably 367± "
North end of Riker Hill	k 1.	378± "
About Caldwell	h 4.	385–390 "
West of Haledon	h 3.	405 "
North of Upper Preakness	h 2.	412 "

* These designations refer to the descriptions, and to the large map of Lake Passaic.

On Long Hill and the Moraine.

North of Lyons station	c 15.	364 feet.
Half a mile south of Lyons	c 12.	361 "
Millington	c 11.	361 "
Long Hill village	c 8.	361 "
One and a half miles northeast of the above	c 5.	361–3"
Northwest of New Providence	C 2.	365 "
End of Long Hill near Chatham	C 1.	369 "
West of Madison	probably	373 "
West of Convent	"	374 "
Morristown	"	376 "

These figures show that there is an increase in the elevation of the shore lines from the southern to the northern end of the lake from 345 to 412 feet, a total rise of sixty-seven feet in thirty miles, or two and one-quarter feet per mile. This increase is by no means regular. Within short distances, the gradient varies from nearly four feet per mile to less than one foot. In one or two instances, notably along the subaqueous overwash plain, the shore line, after making all possible allowances, seems to be slightly lower than at points farther south and southwest. But in spite of these variations and apparent contradictions, generally speaking, the shore lines can be said to rise constantly from the southward to the northward end of the lake, at an average rate of two and a quarter feet per mile.

An outline map of the lake basin is given in Figure 11. On this map there have been drawn isobases at intervals of five feet. These isobases are lines drawn through points which have suffered equal amounts of deformation. These lines are necessarily hypothetical to a large extent, but they are useful in indicating, so far as can be determined, the nature and direction of post-lacustrine changes of level. The direction of these lines indicates graphically several important points. The great differences in the rate of rise of the shore lines in different localities is clearly shown by the varying distances of the lines from each other, the rise being more rapid where the lines are close together. Irregularities in rate of rise are also brought out by the curves of several of the lines. It is further seen that the shore lines do not rise most rapidly in the direction of the longer axis of the lake, but rather from south to north. Calculated in this direction, the rise is sixty-seven feet in twenty-five miles, or a gradient of two and two-thirds feet per mile.

The explanation of the greater northward elevation of the shore lines may be sought along two lines. 1°. The great mass of ice which covered all the country to the north of Lake Passaic must have exerted some attractive force upon bodies of water along its margin. The tendency of such attraction would be to draw away the water from the end of the lake farthest removed from the ice, and to raise its level at the other end. The shore lines, therefore, would not be horizontal in reference to the present sea-level, but would rise to the northward.

To what extent can the changing elevation of the shore lines of Lake Passaic be referred to this cause? If the northward rise of the shore lines were due solely to this cause, the rate of rise for each mile should be constant, or should increase by a regularly-changing increment. The northward elevation ought to be represented by an upward-slanting, straight line, or by a regular curve, concave upward. A study of the shore elevations as given above, or of the position of the isobases in Figure 11, will show that this is not the case but that the gradient changes irregularly from place to place. Further than this, it has been shown* that, under the most favorable conditions which could possibly have existed during the glacial period, as respects ice mass and bodies of water free to be attracted, the amount of elevation of the surface of the water could not have exceeded a half foot per mile. It is extremely probable that in the case of a small body of water like Lake Passaic the rise of the water towards the ice was much less than this. Manifestly, therefore, this hypothesis is quantitatively insufficient. Nevertheless, the ice mass doubtless had some effect in raising the level of the waters of the lake along its northern side. As an accessory factor it must not be neglected.

2°. The other explanation of the present altitude of the shore line is to be sought along the line of crustal deformation in post-lacustrine times. The doctrine of isostasy has found much favor with geologists in recent years. The theory that the crust of the earth is sensitive to changes of load seems to be borne out by many facts which have come to light in the last few years, and by many others which have but recently been studied from this standpoint. It has long been recognized by geologists that the crust of the earth was somewhat

* Chamberlin and Salisbury, Sixth Annual Report U. S. G. S., page 291, *et seq.* The mathematical calculations are by R. S. Woodward.

depressed beneath the weight of the ice cap of the glacial period. The exact amount of this depression is unknown, chiefly since geologists are very far from an agreement as to the pre-glacial elevation of the land. The depression was presumably greatest towards the north, where the thickness and weight of the ice were greatest. On the withdrawal of the ice sheet the land tended to regain some-

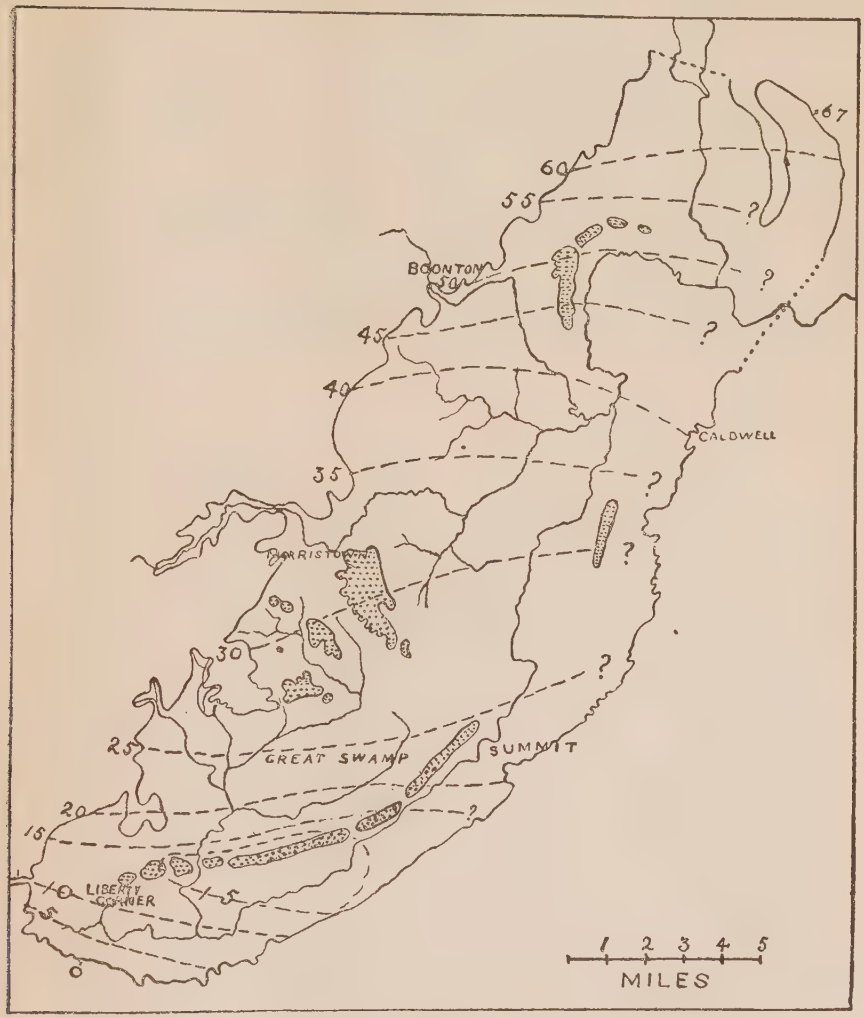

Fig. 11.

The broken lines are isobases. The numbers upon them represent their height in feet, above the south end of the lake. Dotted areas represent islands.

thing of its original elevation. The resilience was probably differential, as the subsidence is thought to have been. On the doctrine of isostasy, the rise would be expected to be greatest at the north. It is not to be expected that such an elevation would proceed with a constant gradient. It would rather be of the nature of an irregular warping, with the greatest rise to the northward. The irregularities of rise might well be such, that locally there were areas which failed to rise so much as other areas farther south.

The studies by Gilbert, Spencer, Upham, Leverett and others of the higher shore lines of the glacial ancestors of the Great lakes, and by De Geer of the deformed sea-beaches along the north Atlantic coast, leave no doubt as to the changes of level of the earth's crust during and since the glacial epoch. It was to be expected that the shore lines of Lake Passaic would show unmistakable evidence of similar changes of level. The northern half of Lake Passaic basin, together with all the country north of the moraine, was weighted down beneath the load of ice. In addition to the ice there was the much lesser load of drift, which toward the ice margin, and particularly in the area of the lake basin, attained considerable thickness. In the extra-morainic portion of the basin there was in place of the ice load, the load of water and of the lacustrine deposits. Beneath the weight of these various elements, but chiefly the mass of ice, the crust of the earth sank differentially, the amount of sinking being greatest to the north, where the load of ice was greatest. The area south of the ice, and south of the water of the lake was probably depressed also, but to a less extent than the country farther north, on which lay the load which caused the depression.

The resilience of the land, after the melting of the ice, and for this particular region after the draining of the lake, tended to restore it to its original altitude. The shore lines of Lake Passaic were tilted by varying amounts. Although the average gradient from south to north is two and two-thirds feet per mile, it is sometimes as high as four feet per mile, while in one or two instances and for short distances the shore lines descend slightly to the northward.

The deformation of the shore lines occurred after the lake was drained, rather than during the different stages of the lake. This is shown by the fact that the Upper Preakness shore line is everywhere about seventy feet below the Montville level, whereas, if any

deformation had occurred in the interval between these two stages, their shore lines would not be essentially parallel.

The gradient of the warped shore lines of Lake Passaic is high, but it is not higher than that of some other glacial lakes. Baron De Geer * in his studies on post-glacial warping, chiefly along the New England and St. Lawrence coasts, found a gradient varying from 2.70 to 1.07 feet per mile. The differential elevation of the Iroquois beach around the eastern end of Lake Ontario is five feet and more per mile.† The highest of the many beaches observed around the glacial Lake Agassiz has now a northward ascent of about thirty-five feet in the first seventy-five miles, sixty feet in the second seventy-five miles, and about eighty-four feet in the third distance of seventy-four miles, a total of 175 feet in 224 miles. These gradients vary from slightly less than one-half foot to more than one foot per mile. The tilting which deformed the Nipissing beach of the second Lake Algonquin ‡ varies from a half foot to a foot per mile. The gradient which has been shown to exist within the Lake Passaic basin lies about midway between the maximum and minimum quoted above.

ECONOMIC VALUE OF LAKE PASSAIC.

Gravel deposits.—As has already been shown, the shores of Lake Passaic are marked by beds of gravel. In the extra-morainic basin the gravel is usually trap, occasionally red shale, more rarely gneiss or quartzite. The value of these deposits as sources of supply for road material has to a limited extent been recognized, and pits have been opened in a number of them. The trap gravel by reason of its abundance, its durability and its angular character, is by far the best of the gravels for road purposes. The pebbles or fragments, although distinctly water-worn, are not much rounded and pack firmly, making a hard, substantial roadbed. Besides the well-defined beds whose location is shown upon the accompanying map, surface indications of gravel have been observed along the shore line at many places, particularly in the timber. It is quite probable that much more gravel

* Proceedings of the Boston Society of Natural History, Vol. XXV., pages 454–477.

† Upham. Bulletin of the Geological Society of America, Vol. II., page 260.

‡ Taylor. American Geologist, Vol. XV., page 117.

exists than has been accurately located. The places where it is to be sought are along the old shore lines. It is entirely within bounds to assert that there is enough trap gravel around the extra-morainic shores of Lake Passaic to macadamize all the roads within that part of the area. The glacial gravel along the moraine and within the lake basin north of the moraine is used to some extent upon the roads. It is, however, inferior to trap gravel, chiefly because of the large percentage of sand which it commonly contains.

Lacustrine clays.—The clays within the lake basin are used to some extent in the manufacture of brick, rough pottery and tiling. The most extensive brickyards are those south of Morristown, those northwest of this place, and those between Little Falls and Mountain View. The supply of clay within the lake basin, particularly in the Great swamp area, is practically inexhaustible. It is not all equally good, but there is much which is of as good quality as that used in the brickyards near Morristown. Unfortunately, it is not all so available.

The swamp areas.—If the land were to be restored to the altitude possessed during the lake period, the restoration would involve a depression of fifty feet at Little Falls, and about the same at Boonton. Under these conditions the swamp areas of the lake basins would be greatly changed. The submerged or partially-submerged lands north of the moraine, along the Whippany and Passaic rivers, would at once be drained and transformed from swamps to rich alluvial bottom lands. The Great swamp area would be differently affected, since its drainage is held at its present level by the obstruction (trap rock) in the river at Millington. If the land were restored to its glacial altitude, this would not be lowered but, on the contrary, would be raised relatively to the swamp. Such a northward depression might convert the lower parts of the Great swamp area into a shallow lake.

The swamps and meadows along the Passaic river north of the moraine are conclusive proof either that the Passaic river does not now flow in its pre-glacial channel across the trap ridge at Little Falls, or that the post-lacustrine elevation so tilted the land, that the river has not yet had time to cut down its trap bed at Little Falls to the extent of the differential rise at this point. Until this is done the swampy land will not be drained. No data are at hand concerning a pre-glacial channel at Little Falls other than the present course of the river. The facts, so far as they are known, indicate that such a

buried pre-glacial channel, even if it exists, is probably not so deep as the buried Short Hills valley. The loss of arable land either through the blocking of a pre-glacial channel across the trap, or through the warping of the lake basin, or through their combined action, amounts to many thousand acres. A part of this, however, will soon be reclaimed on the completion of the work of blasting away the rock barriers at Little Falls, a work which has been going on for several years.

INDEX.

INDEX.

PAGE

Advance of the ice 62
Amount of differential elevation of the shore lines 77
Area of Lake Passaic 75
Baird, A. H., clay concretions found in well 47
Basking Ridge, shore features near 15, 21
Berkeley Heights, shore features near 19
Bernardsville, shore features near 11, 15
Boonton glacial delta 34
Caldwell shore terraces 41
Chatham terrace 16
Clay deposits 45, 49, 82
Convent station, overwash plain near 25
Cook, Prof. Geo. H. 3
Cross-sections of Lake Passaic 61
Currents, direction of 30
Davis, Prof. Wm. M. 3
Dead lake 57, 73
Deformation of the lake basin 75
De Geer, Baron 80, 81
Deltas in the extra-morainic part of the lake 31
Depth of Lake Passaic 75
Draining of Lake Passaic 75
Durie spit 17
Economic value of Lake Passaic 81
Elevations, table of 76
Extra-morainic basin 6
Gilbert, G. K. 80
Glacial deltas 67
  Near Boonton 34
    Haledon 40
    Jacksonville 38
    Montville 36
    Parsippany 34
    Upper Preakness 39
Glacial terraces near Caldwell 41
Gravel deposits, economic value of 81
Great Notch 58
Great swamp, clay in 45

PAGE.

Haledon terraces..... 40
History of Lake Passaic..... 62
  Summary of..... 74
Hook mountain, shore features on..... 42
Iceberg deposits..... 44, 49
Intra-morainic basin..... 7, 31
Isostatic changes of level..... 78
Iroquois beach..... 81
Jacksonville glacial delta..... 38
Kettle-holes in the overwash plain..... 25
Lacustrine deposits..... 44
  Economic value of..... 82
Lake Algonquin..... 81
Lake Agassiz..... 67, 81
Length of life of Lake Passaic..... 74
Leverett, Frank..... 80
Liberty Corner, shore features near..... 10, 14, 20
Liberty Corner outlet..... 51
Little Falls gorge..... 57
Littleton, shore features near..... 34
Livingston, shore features near..... 33, 42
Long Hill, shore features on..... 12, 13, 14, 16, 18
Lyons station, shore features near..... 20, 21
Madison, overwash plain near..... 25
Madison stage of Lake Passaic..... 65
Map showing the warping of the shore lines..... 79
Millington gorge..... 54
Millington, shore features near..... 19
Modified till in the lake basin..... 50
Moggy Hollow outlet..... 5, 51
Montville glacial delta..... 36
Montville stage of Lake Passaic..... 70
Morristown, shore features near..... 11, 22, 23
Mountain View, clay deposit near..... 50
New Providence, shore features near..... 17
New Vernon, shore features near..... 22
Nipissing beach..... 81
Orange mountains..... 4
Outlets of Lake Passaic..... 51
  Sub-glacial..... 70
Pompton, shore features near..... 39
Pre-morainic Lake Passaic, possibilities of..... 63-65
Retreat of the ice..... 66
Salisbury, Prof. Rollin D..... 3, 4
Shore features of Lake Passaic..... 9-44
  Summary of..... 27, 42
  Table of elevations of..... 76
Short Hills gap..... 5, 58

PAGE.
Spencer, Dr. J. C. 80
Spits 17, 19, 33, 34
Sproul, C. F. 4
Stanley outlet 56
Subaqueous overwash plain 24–27
Summary of the history of the lake 74
Summit gap 60
Swamp areas, economic value of 82
Upham, Warren 67, 80
Upper Preakness glacial delta 39
Stage of Lake Passaic 68
Vermeule, C. C. 3
Wave-built shore features 14, 33
Wave-cut cliffs and terraces 10, 32
West Summit, overwash plain 25